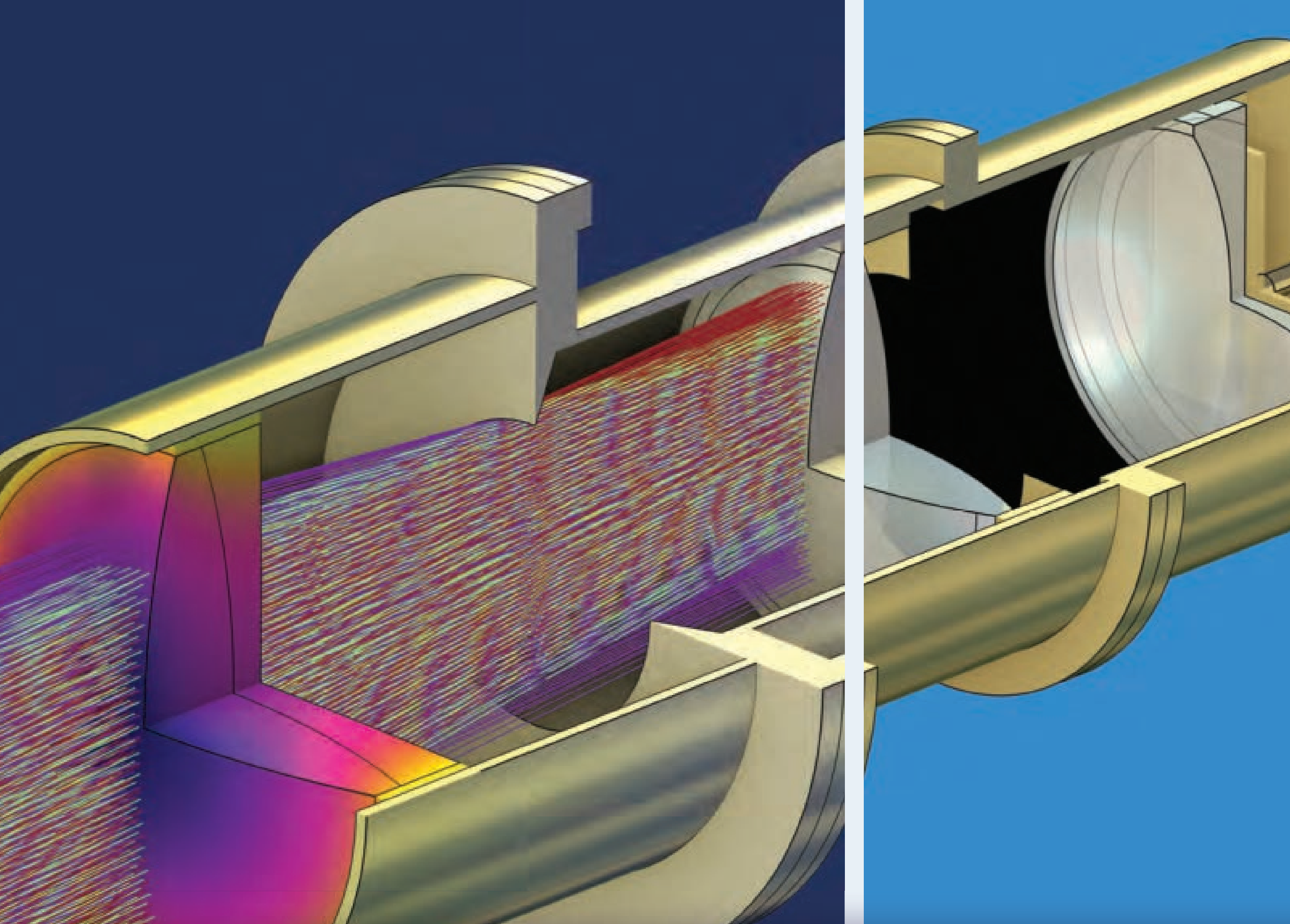

PHYSICS TODAY

October 2023 • volume 76, number 10

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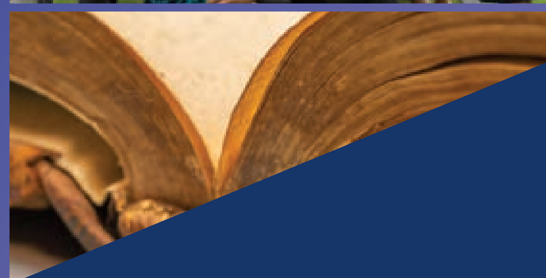
Annual **careers** issue

Exotic iron gives insights into Earth's core

An 18-minute radio-astronomy mystery

Small lakes versus giant ice sheets



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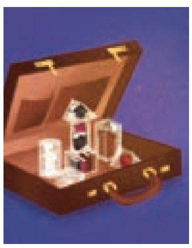

ON THE COVER: Our fifth annual careers issue focuses on the road to tenure. On **page 26**, Eugenia Etkina presents a new way to train future physicists. On **page 36**, Rachel Ivie and Susan White analyze factors that can affect the time to tenure. On **page 44**, Toni Feder explores the impact of not getting tenure. Additional stories report on changing ways to assess researchers' job and grant applications (**page 22**) and on the state of the US radiation workforce (**page 18**). (Image by Abigail Malate.)

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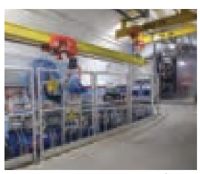

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Neutrinos at the LHC

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A lost detail in D–T fusion history

In the summer of 1942, at J. Robert Oppenheimer's "luminaries" meetings, Emil Konopinski proposed the introduction of tritium into deuterium fuel to enhance the feasibility of a fusion-driven super bomb. Several histories and memoirs by Manhattan Project scientists mention Konopinski's insight, but none that we could find explain where it came from. In one interview, Konopinski stated, "I happened to know from prewar work that the reaction of deuterium with hydrogen-3 produces much more energy and has a larger cross section, so to speak—happens more easily—than deuterium with deuterium."[1] The recent ignition of a D–T mixture at the National Ignition Facility by inertial-confinement fusion (see "National Ignition Facility surpasses long-awaited fusion milestone," PHYSICS TODAY online, 13 December 2022) prompts the question: How did Konopinski, and perhaps other physicists, know about the unexpectedly high D–T reaction rate?

Enter Arthur Ruhlig, who did graduate work at the University of Michigan in the 1930s with H. Richard Crane. They studied electron and positron propagation through lead.[2] In the same year that Ruhlig submitted his dissertation, he published a letter in *Physical Review* assessing whether ^{3}He possesses excited states.

Ruhlig did not detect any excited-state signal, consistent with present understanding. But the title of the letter, "Search for gamma-rays from the deuteron-deuteron reaction," cloaks the tectonic finding of its penultimate paragraph: The reaction $^3H + {}^2H \rightarrow {}^4He + n^1 + 17.6$ MeV "must be an exceedingly probable one."[3] Ruhlig deduced the presence of energetic neutrons, correctly ascribing their production to secondary, in-flight D–T fusion reactions following the $^2H + {}^2H \rightarrow {}^3H + {}^1H$ primary reactions and quantifying the

EMIL KONOPINSKI in Ann Arbor, Michigan. (Photograph by Samuel Goudsmit, courtesy of the AIP Emilio Segrè Visual Archives, Goudsmit Collection.)

rate of the D–T reaction relative to that of D–D. That remarkable observation had never been explicitly cited before.

While working at Michigan on his doctoral degree with George Uhlenbeck, Konopinski overlapped with Ruhlig. (Uhlenbeck is warmly cited in Ruhlig's thesis acknowledgments.) Ruhlig's proximity to Konopinski at Michigan and his inclusion in reference 3 of a citation to a private communication from Hans Bethe—who worked with Konopinski at Cornell University—afford possible conduits for the key piece of surprising information on D–T fusion. A follow-up measurement confirmed the large cross section.[4]

As the story of nuclear-reaction physics continues to unfold, we hope to uncover more of its historical details,[5] hopefully with input from readers of Physics Today.

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Plutonium pits and moral principles

I commend David Kramer for his Issues & Events piece "Despite unknowns, NNSA plunges ahead on plutonium pits" (Physics Today, April 2023, page 22). But it is missing a discussion of the morality of possessing nuclear weapons in the first place.

Both rightness and truth are important. Many US citizens, including those with and without physics backgrounds, do not want their federal taxes to pay for nuclear weapons—and therefore National Nuclear Security Administration facilities that aim to make, certify, or store them. And voters' decisions in national elections can be flawed if based on misinformation.

The public also needs information from the National Nuclear Security Administration regarding the stability of plutonium pits, especially given the conundrum of the element's instability from the mutually interacting effects of self-irradiation and its multiple phases—to say nothing about the other properties of plutonium (for example, that it is pyrophoric when in contact with air).

Everyone needs to be included in devising solutions to the problem of nuclear weapons. If those with moral reservations are excluded from that work, the results will be flawed.

Harold M. Frost III
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Shorten the solar-geoengineering timeline?

In his article on climate tipping points, Michael Edgeworth McIntyre highlights how the various synergies among contributing factors mean there are multiple possible pathways toward unpredictable adverse climate impacts (Physics Today, March 2023, page 44). Only a subset of those pathways need to be self-reinforcing in an adverse way to produce more severe or more abrupt harmful outcomes than models predict.

In that context, it can be useful to reconsider the role of solar-radiation management (SRM), also known as solar geoengineering—a strategy that involves reflecting some of the Sun's energy back into space as a means of combating climate change. Proposed SRM strategies include the injection of aerosols into the atmosphere, the brightening of marine clouds via sea-salt injection, and even the creation of floating mirrors in space.

The well-known potential drawbacks of those strategies should be viewed in the context of growing indications that climate degradation will outpace decarbonization. McIntyre's survey of climate contingencies serves as a reminder that the decision of whether to implement SRM is a choice between the lesser of two problematic scenarios.

In that regard, two points are pertinent. First, the choice is not binary. A limited deployment of SRM that fractionally slows the global-temperature increase over several decades might yield benefits that greatly outweigh the associated risks. Second, the possible rapid onset of extreme climate scenarios could accentuate the need for timely SRM deployment, which raises the question of how quickly that need could be met. The present approach, which holds more-concrete steps in abeyance pending the outcome of ongoing studies of SRM effectiveness and drawbacks and the clarification of governance, could mean that we wouldn't see any tangible mitigation benefits for decades. Aerosol dispersal, for one, will eventually require the design and construction of aircraft, among other large-scale industrial tasks.

The adverse impacts of that lag could be enormous. Parallel efforts, analogous to the COVID-19 vaccine development strategy, therefore merit consideration. That would involve initiating long-lead-time substantive preparations for deployment concurrently with scientific evaluation, but not committing to full operational deployment of SRM capability until it has been adequately assessed with regard to its effectiveness and risks. By that or other means, the prioritization of SRM should be aligned with its unique precautionary role.

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A journey to Earth's center, courtesy of an exotic iron crystal

Laboratory experiments are helping researchers get closer to solving some of the mysteries of the solid inner core.

No one has ever seen Earth's core. Artists' impressions such as the one in figure 1 are thankfully confined to the realm of the imagination. Everything that's known about Earth's deep interior structure comes from indirect observations, such as the speeds and trajectories of seismic waves that propagate from one side of the planet to the other. From such seismic measurements, researchers deduced decades ago that the outer core of liquid iron surrounds an inner core that, although hot enough to melt, is compressed into solid form.

But there's a sticking point to the interpretation of seismic data: Laboratory researchers haven't been able to measure the elastic properties of the hot, pressurized form of iron that makes up the inner core. Replicating inner-core pressures and temperatures, by themselves, isn't such a problem. But as metalworkers have known for centuries (see the Quick Study by Lou Bloomfield, Physics Today, May 2007, page 88), iron's material properties depend on more than its instantaneous pressure and temperature. They also hinge sensitively on its impurity profile and its past history of being heated, cooled, pounded, and squeezed.

Now Agnès Dewaele, of the French Alternative Energies and Atomic Energy Commission, and her colleagues have achieved a milestone in inner-core metallurgy. They've synthesized a single crystal of ε-Fe—the form of iron that's stable under the extreme conditions of the inner core—that's clean enough to measure its elastic constants.[1]

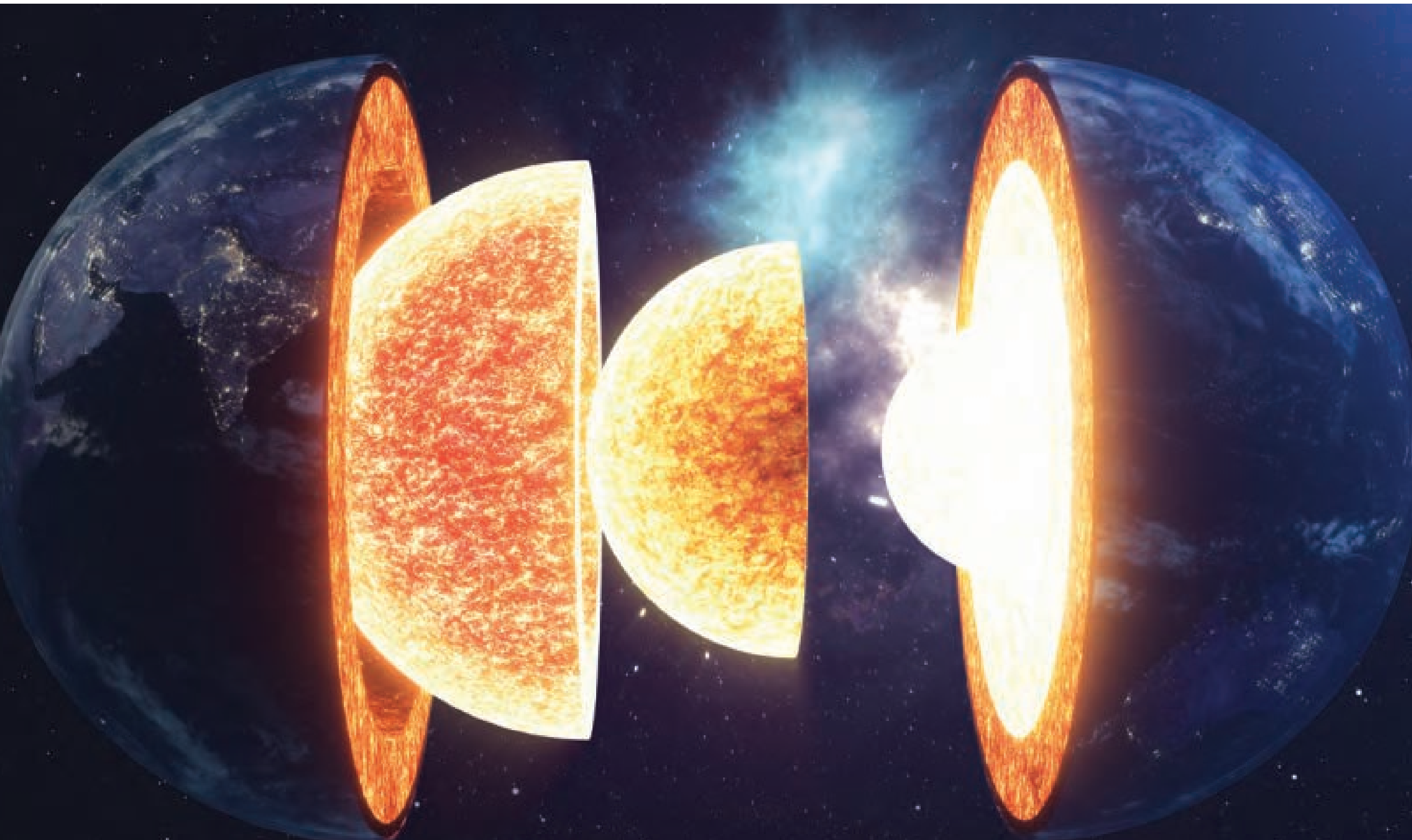

FIGURE 1. WHITE HOT SOLID IRON—with a bit of nickel and some other elements—lies at the center of our planet. By re-creating its high-pressure crystal structure in the lab, researchers hope to better interpret the seismic measurements that are the source of most of what's known about the inner core. (Image by Rost9/Shutterstock.com.)

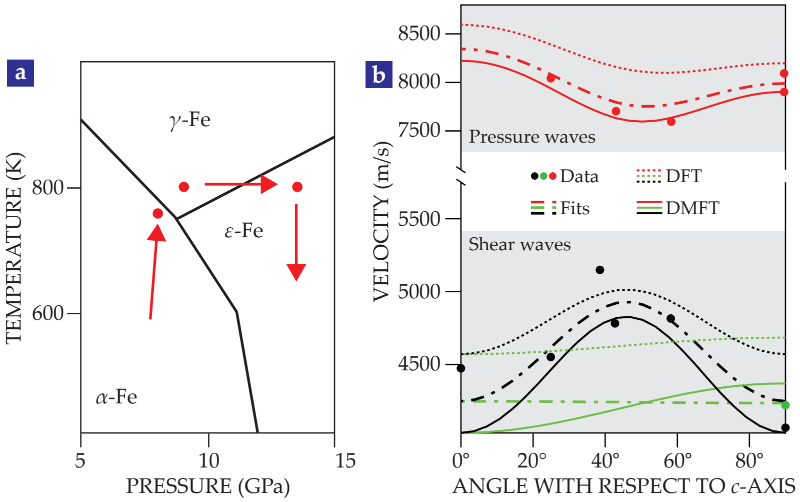

FIGURE 2. SINGLE CRYSTALS of ε-Fe, the form of iron thought to exist in Earth's inner core, can't be made by directly squeezing the ambient-pressure phase α-Fe. **(a)** But they can be made by taking a detour through the high-pressure phase γ-Fe, as shown in the path in red. **(b)** Sound-speed measurements on ε-Fe single crystals clearly show the material's elastic anisotropy, and they provide a valuable benchmark for theoretical models such as density functional theory (DFT) and dynamical mean field theory (DMFT). (Adapted from ref. 1.)

The experiments don't yet replicate the temperature, pressure, or impurity profile of the inner core, so they're still several steps away from pinning down the sound speed through real inner-core material. But they provide a much-needed benchmark for theoretical models, and they pave the way for more experiments to get close to inner-core conditions.

Forged in fire

The inner core is mysterious in many ways. (See the article by Bruce Buffett, Physics Today, November 2013, page 37.) One of its most striking features, discovered in the 1980s, is that it's anisotropic: Seismic waves traveling from pole to pole traverse the inner core about 4% faster than those that originate along the equator.

The large-scale anisotropy doesn't necessarily mean that inner-core iron is structurally anisotropic at the atomic scale. It could be explained, instead, by the large-scale distribution of materials with different impurity concentrations. But as it turns out, ε-Fe's crystal structure is hexagonal close packed, which is in fact anisotropic: One of its crystal axes, the *c*-axis, is geometrically distinct from the other two.

Although the inner core probably isn't one single crystal of ε-Fe, it could be made up of component crystals that are preferentially aligned. Deciphering what that alignment looks like—and how it might have arisen—could offer substantial insight into Earth's geologic past. But it also requires an understanding of ε-Fe's anisotropic elastic properties. And those measurements are hard to come by.

Pristine ε-Fe is extremely difficult to make in the lab. The naive approach—taking a single crystal of the ambient-pressure form of iron, α-Fe, and trying to compress it into ε-Fe—doesn't work. The α-Fe crystal splinters into a myriad of tiny ε-Fe crystals too small to study individually. Worse, their crystal lattices are strained and distorted, so their properties probably differ considerably from those of unstrained ε-Fe.

Typical lab studies of ε-Fe, therefore, usually use polycrystalline samples made from compressing α-Fe powder.[2] That approach yields a lot of useful information. But it obscures the crucial distinction between the single crystal's *c*-axis and the other two dimensions.

A different path

Dewaele came to the problem from a different direction. She was initially interested not in ε-Fe's material properties but in the mechanisms of iron phase transformations.[3] In addition to α-Fe and ε-Fe, there's also the γ-Fe phase, which iron adopts at high temperature, as shown in figure 2a. The three phases meet at a triple point, so each can be transformed into either of the others.

"We were using x-ray diffraction to monitor the fate of a single crystal," she says, "when we noticed that the alpha–gamma transformation produced a completely different microstructure—and crystal quality—than alpha–epsilon." Dewaele and colleagues soon worked out that by first heating the α-Fe into γ-Fe and then compressing it into ε-Fe, they could prevent most of the crystal splintering of the α–ε transformation. They still got polycrystalline ε-Fe, but some of the crystals were sufficiently large and unstrained to study. "We became very excited about measuring ε-Fe's single-crystal elastic constants, which we knew was important and never done before," she says.

Like most researchers studying static high pressures, Dewaele and colleagues squeezed their sample using a diamond anvil cell, which works by concentrating modest forces into a small volume. As a result, they were limited to speck-sized iron samples—just 60 μm across—and their "large" ε-Fe single crystals were a mere 20 μm across.

That might not seem like it would be big enough for measuring a crystal's mechanical properties such as elasticity and speed of sound. But thanks to x-ray inelastic scattering, it is. When an x-ray photon passes through a crystal and excites a vibration, it loses energy and changes direction according to the vibration's frequency and momentum. By analyzing the pattern of scattered x rays, researchers can determine the crystal's quantized spectrum of vibrational modes, and from that, they can deduce its elastic properties and speed of sound.

Dewaele reached out to x-ray inelastic scattering expert Alexei Bosak, of the European Synchrotron Radiation Facility, to secure beam time and make the necessary measurements. The sound-speed results, shown in figure 2b, reflect the various ways that waves can propagate through the crystal: at any angle with respect to the *c*-axis, and as either longitudinal pressure waves (in which the atoms vibrate parallel to the direction of wave propagation) or two kinds of transverse shear waves (in which they vibrate in one of the two directions perpendicular to the direction of wave travel).

The data points, so far, are sparse and scattered. But they show a clear trend of anisotropy: Shear waves are at their fastest, and pressure waves are at their slowest, at an angle of 50° to the *c*-axis. And the fits to the data provide a test for theoretical calculations, such as the density functional theory (DFT) and dynamical mean field theory (DMFT) results shown in the figure.

Smaller and larger

The experiments were performed at room temperature and pressures up to 33 GPa, a far cry from the 5600 K and 330–360 GPa of the inner core. The pressure difference, in particular, is significant. Applying that much pressure to a material, even a solid, squeezes its atoms more tightly together and boosts its sound speed by thousands of meters per second.

Diamond anvil cells can achieve inner-core pressures, but only for samples much smaller than the ones Dewaele and colleagues needed to create their 20 μm ε-Fe single crystals. But 20 μm isn't a fundamental limitation; it's a consequence of the constraints of their experimental system. As Dewaele explains, "If, in the future or on other platforms, inelastic x-ray scattering can be performed on smaller single crystals, then we can extend the measurements to higher pressures." Indeed, the beamline they used at the European Synchrotron Radiation Facility is undergoing an upgrade to focus the x-ray beam to a smaller spot.

Pressure and temperature aren't the only gaps that need to be bridged. The experiments, like the phase diagram in figure 2a, involved pure iron, whereas the inner core probably contains some nickel and other impurities. "Alloying could affect the stable phase," Dewaele points out, so the inner-core material might not have the hexagonal close-packed ε-Fe structure at all. Even if it does (which seems likely), the sound speeds of pure and alloyed iron could be significantly different. "It would surely be very interesting to repeat the experiments with an iron–nickel alloy," says Dewaele.

Ultimately, the goal is to connect the small-scale elastic anisotropy of inner-core material to the known seismic anisotropy of the inner core as a whole to deduce the inner core's internal structure: How big are its component iron–nickel crystals, and how are they arranged? From there, researchers hope to learn more about the geologic history of Earth's depths and deep past.

But Dewaele is already wondering what other undiscovered single crystals might yet be synthesized through careful attention to phase-transformation mechanisms. "I am convinced that for many metallic systems, solid–solid transformations under high pressure can produce microstructures with outstanding properties," she says. "One could call this metallurgy of the extremes."

Johanna Miller

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An unexplained, long-period radio-transient discovery

For 30 years the periodic radio emission from the mysterious object was being observed while remaining undiscovered.

Natasha Hurley-Walker didn't set out to find long-period neutron stars. In 2020 she received a Future Fellowship, a multiyear grant from the Australian Research Council designed to give midcareer researchers the financial flexibility to explore new projects. For Hurley-Walker, of the International Centre for Radio Astronomy in Australia, it was a chance to break free of established ideas and the pressure to publish. She decided that she was "going to throw everything at every wall . . . and see what sticks."

One of Hurley-Walker's exploratory projects involved using data from an Australian radio telescope—the Murchison Widefield Array (MWA), seen in figure 1—in a new way. Instead of using the typical data-processing method, which is optimized for making deep images of the sky, she took a shot in the dark and invented a new technique to find transient radio sources, objects that appear and disappear over time. She followed that path even though previous studies had drawn a blank at radio frequencies.

Hurley-Walker's undergraduate student Tyrone O'Doherty compared data that were as similar as possible: the same area of the sky, the sky in the same position relative to the horizon, and the same RF bands. The only changes that should be found between images are the uncontrollable variations, such as the background signal from the ionosphere. One observation is subtracted from the other, and an image is made of the result. All the sources that do not change simply disappear, leaving only those that have changed. When Hurley-Walker examined a difference image from one region of the sky, she saw a strong signal of an object that's now known as GLEAM-X J1627.[1]

Freedom to explore

GLEAM-X J1627 pushed at the boundaries of what should be possible for a pulsar, a type of neutron star. Pulsars are like cosmic lighthouses: The rotating stars shine a beam of radio emission toward Earth with periods that usually fall between 1 ms and 12 s and last for decades. With its period of 18 minutes, the object was much slower than a typical pulsar. GLEAM-X J1627 didn't persist for a long time, lending credence to the alternative explanation that it was a type of neutron star known as a magnetar, which is powered by strong magnetic fields and emits for only a few months.

Without enough data, though, the researchers couldn't say for sure. So Hurley-Walker designed a dedicated observing project to search for more long-period pulsars. She and her postdoc Tim Galvin automated their data analysis code to better handle the large amount of data they anticipated collecting from the MWA. With another undergraduate, Csanad Horvath, Hurley-Walker worked to improve their detection techniques.

In August 2022, after only a couple weeks of observing, they found GPM J1839-10, their second strange object.[2] Because it had an even longer period of 22 minutes and a radio brightness exceeding other pulsars at similar RF bands, Hurley-Walker wasn't sure it was even a neutron star. But before she jumped to any conclusions, she went hunting for more data.

Lost in the library

Pulsars are extraordinarily consistent and persistent. If GPM J1839-10 is a pulsar, it should be detectable in archive data. Hurley-Walker reached out to Scott Hyman, an emeritus professor at Sweet Briar College in Virginia, to assist with the archival search. Hyman is no stranger to inexplicable long-period transients, having found his own such object, with a 77-minute period, in 2005.[3] More than a decade later, no theory can fully explain what he found.

Hyman and Hurley-Walker began a search not only in the MWA archives but also in those of other radio telescopes, and they made new observations with an x-ray telescope—the European Space Agency's *XMM-Newton*—and an optical telescope. Unlike GLEAM-X J1627, which emitted detectable radio waves for only a few months, GPM J1839-10 showed up in data from as far back as September 1988, at nearly the beginning of digital radio telescope records. Because of the varying interval of time between observations, sometimes only a single pulse was detected and often without great resolution.

Although GPM J1839-10 is bright, it was undiscovered until now because of how astronomers search for pulsars. Pulsars are expected to have short periods, so astronomers look for them by searching for changes on time scales of milliseconds to seconds. With her new method designed to search for long time-scale changes, Hurley-Walker could find objects that changed brightness even if they had longer periods. The technique would not have been possible without modern image processing to analyze the large amounts of data covering a large area of the sky, the configuration of the MWA antennas to provide greater spatial-frequency coverage than other radio telescopes, and the stability of the MWA telescope to allow GPM J1839-10 to stand out against background noise.

Something old, something new

Faced with two ultralong-period pulsars—and a handful of objects with other anomalous properties (see figure 2)—Hurley-Walker wanted to figure out whether the objects were even neutron stars.

A pulsar produces luminous beams of light via pair production: the generation of electrons and positrons from the rapid rotation of the neutron star and its magnetic field. That same magnetic field expels luminous bursts of radio energy. (To learn more about the physics of neutron stars, see the article by Lars Bildsten and Tod Strohmayer, Physics Today, February 1999, page 40.) Based on the current understanding of pulsar models, however, GPM J1839-10 is not rotating fast enough for pair production to occur. Maybe a new understanding of pulsars is needed, or maybe the star isn't a pulsar despite having a regular period over three decades.

Magnetars are similar to pulsars—powerful sources of energy with regular periods—but their energy is provided by a near-constant reconfiguration of their twisted magnetic fields. Although magnetars emit at x-ray wavelengths, *XMM-Newton* did not detect any such emission from GPM J1839-10. The lack of x-ray emission, and the fact that magnetars stop emitting after a few months, has led Hurley-Walker to believe that GPM J1839-10 isn't a magnetar either.

Since the paper was released, Hurley-Walker has talked with other astronomers and come up with new theories. One posits that the star is a white dwarf. By coincidence, Ingrid Pelisoli of the University of Warwick published her discovery of a radio-bright pulsating white dwarf binary system[4] shortly after Hurley-Walker's paper on GPM J1839-10 came out. They learned of each other's

FIGURE 1. THESE ANTENNAS make up one of the 256 tiles in Australia's Murchison Widefield Array radio telescope, which was used in the discovery of ultralong-period radio transients—objects that pulse like cosmic lighthouses. Because of its location, the telescope is able to observe the southern celestial hemisphere.

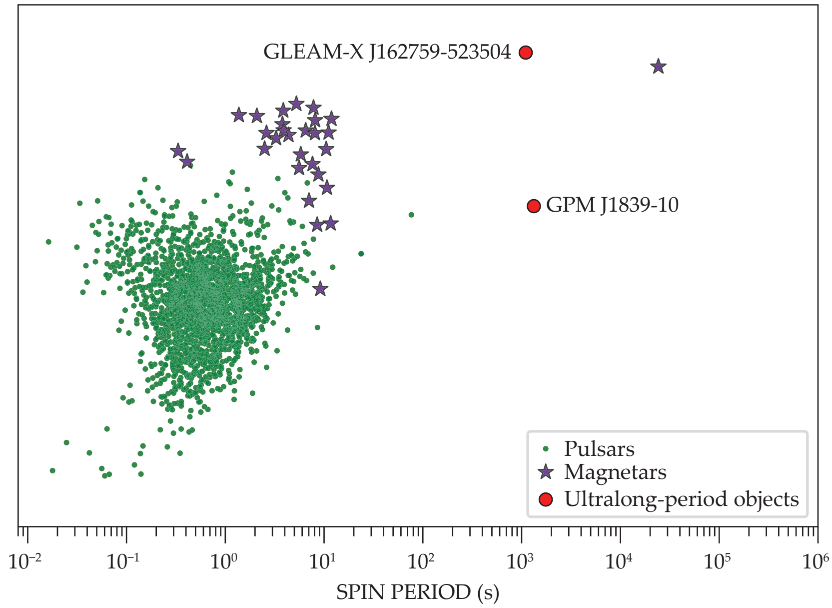

FIGURE 2. THE ULTRALONG EMISSION PERIODS of stars GPM J1839-10 and GLEAM-X J1627 stand out from the cluster of typical neutron stars—pulsars (long-lasting stars with pulsating emission; green circles) and magnetars (characterized by a tangled magnetic field; purple stars). Pulsar periods typically fall between 1 ms and 12 s; magnetar periods typically fall between 2 and 10 s. In addition to GPM J1839-10 and GLEAM-X J1627, only a handful of other astrophysical objects display long periods. Collectively they may be part of a yet-unclassified group of objects. (Data from ref. 2.)

work only when presenting their results at the same conference. The slow rotation and radio emission are promising evidence of a binary white dwarf, but a white dwarf's pulsation is partly powered by the accreting material of its companion star.

Without confirmation of another star, current theories can't explain how such a slow rotator could generate enough electrons to emit radio beams. Follow-up optical observations of GLEAM-X J1627 showed it to be isolated, and GPM J1839-10 has too consistent of a pulse over such a long period of time to be part of a binary system, unless it is perfectly face-on so that no Doppler shift is detectable.

The hunt is on

With no theory to account for all the known properties of the new ultralong-period transients,[5] Hurley-Walker is searching for more clues about what the mysterious objects her team found might be. She has applied for time on the *Hubble Space Telescope* and plans to apply for time on the *James Webb Space Telescope* to get data on GPM J1839-10. Either optical (*Hubble*) or IR (*Webb*) photometry would allow Hurley-Walker to determine the type of star based on how much light is emitted across the spectrum. Unfortunately, it's difficult to observe so close to the galactic plane. The space-based telescopes are the only instruments with enough resolution to fully resolve such a small source in such a crowded region of the sky.

While she waits for observation time on a space telescope, Hurley-Walker continues to use the MWA to look for more such objects. Only six months elapsed between her two long-period pulsar discoveries. In contrast, the first two observations of another type of unusual radio source, the fast radio burst, were four years apart. "Back of the envelope that means that they're not fantastically uncommon." She plans to search at higher galactic latitudes so that the field is less crowded and more telescopes will be able to perform follow-up observations.

Jennifer Sieben

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Alarm sounded over declining US radiation professional workforce

As retirements surge, shortages threaten to slow advances in cancer therapy, diagnostics, and improved understanding of the physiological impacts of radiation.

"We've never had a baby boom before, and we've never seen the loss of such a large proportion of the workforce in such a short time," says Wayne Newhauser, a medical-physics professor at Louisiana State University. Newhauser led the review that makes up the December 2022 special issue of the *Journal of Applied Clinical Medical Physics* (*JACMP*); the review provides a snapshot of the status of the major radiation professional workforces in the US.

Workforce shortages are compounded by newly trained scientists who choose to leave their fields for other opportunities. Charles Ferguson, director of the Nuclear and Radiation Studies Board at the National Academies of Sciences, Engineering, and Medicine, has heard reports of radiation professionals trained at the Department of Energy's Hanford nuclear site in Washington State being snapped up by Amazon and Microsoft for jobs that are unrelated to their field. "People in these professions are smart and trainable, and they can quickly tool up to work in the technology industry," he notes.

A lack of interest from incoming students has led to the closure of many academic programs in most of the radiation specialties, say Newhauser and others, and has resulted in a lack of capacity to train new professionals.

Werner Rühm, who directed Helmholtz Munich's Institute for Radiation Protection until its closure last year, says Germany has also experienced declining interest in radiation sciences. Germany's renunciation of nuclear power has led many people there to conclude that radiation protection is no longer necessary. The country's Ministry for the Environment, Nature Conservation, Nuclear Safety, and Consumer Protection is working to shore up competence in the sciences, in part by communicating its continued importance, Rühm says. "Radiotherapy is the most successful cancer therapy to date. To develop it further, you need competence in radiation science."

The exact size of the professional radiation workforce is hard to determine, in part because of its fragmentation among different fields and its sometimes ambiguous definitions and qualifications. The *JACMP* review, which took the authors seven years to complete on a pro bono basis, includes estimates that vary in fidelity depending on the field; some of the radiation specialties do not keep figures at all.

Health physics

Health physicists aim not only to protect workers, the general population, and the environment from the ill effects of radiation but also to ensure radiation's beneficial uses, which include laboratory research, mining, oil and gas exploration, nondestructive testing, and brewing. The *JACMP* review estimates the health-physics workforce at anywhere from 3200 to 7000 persons, depending on the definition used. The Health Physics Society reported a membership of 3081 in 2020, down from its 4277 members in 2013. Those figures likely understate the actual number of health physicists in the US, the review says.

About half of health physicists in the US work in nuclear power plants, according to the *JACMP* review. The rest are spread across industries where workers use or are exposed to ionizing radiation.

Qualifications for health physicists vary widely. Eligibility for full membership in the Health Physics Society, for example, requires anywhere from a PhD to five years of experience without a formal health-physics degree.

The Nuclear Energy Institute, the trade group for the US nuclear technologies industry, told Newhauser and his coauthors that just 400 of the 3700–3800 radiation protection staff in nuclear power plants are required to have a four-year degree in health physics or a related field.

MEDICAL PHYSICIST Becky Guidry (left), of the Mary Bird Perkins Cancer Center in Baton Rouge, Louisiana, shows trainee Bijoyananda Adhikary how to work with a quality assurance device being used on a diagnostic CT scanner. The images taken by this CT scanner will help in planning computer-optimized radiation therapy that employs x rays or electrons.

Emily Caffrey, program director of the health-physics program at the University of Alabama at Birmingham, says a steady decline in the number of health physicists has occurred over recent decades and has spanned every industry where they are employed. "Shortage is an understatement," she says.

Caffrey and others blame the partial meltdown at the Three Mile Island nuclear plant in 1979 for the plunge of interest in all the radiation-related professions. The accident resulted in a dramatic slowdown in construction of new nuclear plants. Many students at the time felt that


LOUISIANA STATE UNIVERSITY

"nuclear stuff is just going to go away," she says. The 1986 Chernobyl disaster only reinforced that attitude.

But the market for health physicists is strong. Thomas Johnson, a professor of health physics at Colorado State University, runs a job board that lists about 80 openings each month. About three-quarters of the advertised positions require a bachelor's or graduate degree, most often a master's. Many of the postings remain unfilled for months, he says.

Around 18 academic institutions in the US offer accredited bachelor's health-physics programs, the review says. That's roughly half the programs that once existed. Twenty-three institutions currently grant master's degrees and 17 award PhDs.

"All the programs are in trouble with recruiting," Johnson says. "They're all very concerned about being closed for lack of students or lack of funding." Colorado State currently has 15 master's and PhD health-physics students, and the department will be starting an undergraduate program soon in hopes of attracting more students to the graduate level. But the program had to turn away two or three students this year because of inadequate funding.

"The bulk of our students are attracted to or working for the Department of Energy, yet DOE has no funding for training health physicists," Johnson says. DOE's national laboratories employ around 400 full-time health physicists in positions that generally require a bachelor's degree or higher in a related discipline, according to the *JACMP* review. Some funding for health-physics education in the US is provided by the Nuclear Regulatory Commission.

"The biggest problem is getting the word out that this is a job that's interesting, in high demand, and pays well," Caffrey says. "If you were to survey health physicists, a very high percentage would say they found [their careers] by accident or were told about it when they were halfway through a physics degree. People just don't know about it."

Starting salaries for health physicists vary widely, says Johnson. A master's degree holder could make more than $100 000 at a federal facility, while a state agency might offer less than $50 000. "It's highly unusual for a highly qualified student to go to work for a state. So some states have been hiring people with a degree in biology or another science and sending them to training classes to qualify them," he says.

Radiation biology

Already the smallest of the radiation professions, radiation biology is the most endangered, at least in the US, the *JACMP* review says. Jacqueline Williams, a radiation biologist at the University of Rochester and an author of the review, describes the field as seeking to determine the exact impacts of radiation on tissues: "how molecules in the cell react, how the cell reacts, how the tissue reacts, and how the organism reacts." It differs from medical physics, which deals with the application of physics to the diagnosis and treatment of human disease.

Radiation biology has been in decline for about the past 40 years, says Williams, when radiation oncology departments were unable to find enough radiation biologists to train their residents. As a result, the accrediting board dropped its requirement for a radiation biologist to be on staff of those departments. "By just saying we don't need a radiation biologist, they made it worse," she says. "What had been a declining profession suddenly became a dying profession." The change also led to a "watering down" of the radiation-biology component of residents' training, Williams laments.

Further contributing to radiation biology's decline was the termination in 2016 of DOE's long-running research program on the health effects of low doses of ionizing radiation. Congress has ordered DOE to reinstate the program, and House and Senate appropriators have included $20 million in their pending fiscal year 2024 spending bills for that purpose. A 2022 report by the National Academies recommends funding of $100 million per year for that research program.

Retirements continue depleting the ranks of the 500 or so remaining US radiation biologists. The last two formal radiation-biology training programs in the US were closed a decade ago, and Williams says anyone interested in entering the field would need to get into the lab of a qualified biologist who is working hand in hand with a medical physicist.

The decline of radiation biology won't put patients at risk, but it could impede further progress in radiation oncology, Williams says. "Oncologists have become mere applicators; they use their fancy machines [without] necessarily understanding the biology behind them."

Radiation biology is in less dire straits in Europe, says Andrzej Wojcik, a radiation biologist at Stockholm University, home to Sweden's sole radiation-biology program. He's funded by the Swedish Radiation Safety Authority and by Euratom, the international nuclear organization of European Union members. The EU also has a low-dose-radiation research initiative, which helps to keep the discipline alive there.

France and Germany have dedicated research support for radiation biology, as does the nonprofit Cancer Research UK. But Belgium's general radiation-biology program is being refocused on nuclear waste, the environment, and radionuclide terrorism, says Wojcik.

Williams and Wojcik both say that

Aspect	Health physics	Medical physics	Medicine	Nuclear engineering	Radiation biology	Radiation and nuclear chemistry
Size (number of workers)	3200–7000	8000	37 600 (34 000 radiologists, 3600 radiation oncologists)	18 000	~500	Estimate not available
Trends in workforce size	Shrinking	Growing; shortages in some subspecialties	Changing practices in radiology and radiation oncology affecting workforces	Slight growth; aging workforce lacking in diversity	Shrinking; shortages due to aging workforce, failure to replace	Shrinking; shortages due to aging workforce
Factors driving future trends	Closure of power plants	Increasing demand due to population growth/aging	Aging/retirements, employment choices (full vs. part time), use of AI	Increase in nonpower applications (for example, nuclear security)	Aging/ retirements, reduced funding	Aging/ retirements, reduced funding
State of education and training	Small capacity; risk of program closure	Limited residency positions may affect the future pipeline	Adequate capacity	Adequate capacity	Complete loss of training programs	Risk of future inability to maintain the workforce
Future outlook	Poor	Good	Good	Good	Poor	Poor

A SUMMARY of the workforce health of the radiation professions shows several with worker shortages and declines in the number of education and training programs. (Adapted from W. D. Newhauser et al., *J. Appl. Clin. Med. Phys.* **23**, e13846, 2022.)

radiation biologists would be essential in the response to a radiological catastrophe, such as a nuclear bomb or dirty bomb detonation. “There is almost no medical [response] if there is some kind of large-scale disaster,” says Williams. “The physicists can wander around with their meters; the radiation oncologists will hide. It’s the marriage of the biologists and the physicists that will actually guide public health in those circumstances.”

Medical physics and radiology

The International Organization for Medical Physics counts nearly 30 000 medical physicists worldwide. The roughly 8000 members of the American Association of Physicists in Medicine have earned a master’s or doctoral degree in physics, medical physics, biophysics, radiological physics, medical health physics, or equivalent disciplines. Members must also be certified in their specific subfields, which include therapeutic, diagnostic, and nuclear medical physics.

Medical physicists maintain and calibrate the equipment used in diagnostic and therapeutic radiation. They also help to improve the targeting and delivering of radiation to patients and advise radiologists to ensure that a patient won’t receive an excessive radiation dose when multiple x rays or CT scans are ordered. “The physicist needs to be sure to get the amount of radiation to where the oncologist wants it, taking into account a specific patient’s anatomy and the healthy structures around the tumor,” says Lydia Wilson, a medical physicist and assistant professor in the radiation oncology department at Sidney Kimmel Medical College and Cancer Center in Philadelphia.

The medical-physics workforce is currently adequate in size, says the *JACMP* review, but there are indications of shortages developing in some subspecialties, including diagnostic imaging and nuclear medicine. The review notes that although the education pipeline is sufficient for current needs, bottlenecks could result from a shortage of residency training positions.

Newhauser worries that the medical-physics profession won’t be able to respond quickly enough if the need arises. “It may take 5 years to train a PhD, but a fully qualified medical physicist may take 10 to 12 years,” he says.

Several factors, including burnout, a trend to part-time work, and skyrocketing demand for medical imaging, have led to a nationwide shortage of radiologists, says Edward Bluth, chair emeritus of the radiology department at Ochsner Health, a multispecialty clinic in New Orleans. The US “produces about 1200 diagnostic radiologists each year, but larger numbers are leaving,” he says.

Artificial intelligence could alleviate some of that shortage. “If AI makes radiologists more efficient and reduces some of the work we do, then the volume of radiologists may be adequate,” says Bluth.

Nuclear engineers

Nuclear engineers are mainly employed in the design and support of nuclear reactors and the nuclear fuel cycle. In the near term, a reduction in personnel because of recent and upcoming nuclear power-plant retirements is being partially offset by a need for personnel to decommission the plants, the *JACMP* review says. The hiring of young engineers into the existing workforce appears to be sufficient to meet current demand, it states. A gap in mid-level management may soon appear, however, because of the large number of senior personnel who are expected to retire over the next decade.

Shaheen Dewji, an assistant professor of nuclear and radiological engineering and medical physics at Georgia Tech, says the US demand for engineers is growing in the national security sector. She points to the National Nuclear Security Administration’s formation of four large university consortia to create a pipeline that would match trained nuclear engineers and other nuclear professionals with national security needs. Each has a different thrust, including fundamental research, enabling technologies, and arms control monitoring and verification.

Radiochemistry

Radiochemistry traces its roots to the wartime Manhattan Project, when chemists devised methods of separating plutonium from the other components of spent nuclear fuel, says Brian Powell, the Fjeld Professor in Nuclear Environmental Engineering and Science at Clemson University. More than a decade ago, the National Research Council warned of a wave of impending retirements coupled with a dramatic decrease in the numbers of students opting for careers in nuclear chemistry and radiochemistry. The National Academies' Ferguson says it may be time to revisit the workforce issue, although he hasn't yet proposed a study.

Newhauser and his coauthors were unable to estimate how many scientists are working in radiochemistry and nuclear chemistry. The number of training programs has fallen over the past few decades, and today only Florida International University and the University of Nevada, Las Vegas, offer a radiochemistry PhD in the US. Other radiochemists receive their formal degrees in chemistry, so it is difficult to track their numbers.

Today, radiochemists are in demand to work on the environmental cleanup of nuclear waste, in national security, and on research on materials needed for advanced reactors, to name a few areas. The PhD and master's students who are graduating from Powell's program are being hired immediately, mostly by DOE national laboratories.

Addressing the shortages

Newhauser says workforce concerns must be addressed "systematically." He recommends the creation of an advisory board at the national level to make recommendations for the short, medium, and long terms. "What hasn't worked is to leave it to the professionals, . . . DOE and the politicians," he says. Federal funding agencies need to coordinate their efforts. Data on the workforces, education pipelines, and projected needs should be collected and assessed annually to see where attention should be devoted.

At a symposium held in November 2022, the standards-setting International Commission on Radiological Protection (ICRP) called for actions to strengthen expertise in the radiological protection workforce worldwide, including increased government funding for research at universities and national laboratories. The ICRP also urged universities to develop undergraduate and graduate programs and to increase student awareness of job opportunities in radiation-related fields.

Rühm, who now chairs the ICRP, notes that 50 of the group's 360 members are mentees. The students bring new ideas to the ICRP committees and task groups, he says, and their participation helps make the occupations more attractive to young people. Other radiation professional organizations, he suggests, might follow suit.

David Kramer

Global movement to reform researcher assessment gains traction

One aim is to recognize a wider range of research contributions.

A growing global movement toward holistic approaches to evaluating researchers and research aims to value a broader range of contributions than an institute's reputation and such metrics as numbers of publications in high-impact journals, citations, and grant monies. Contributions that go largely unrewarded include committee service, outreach to the public and to policymakers, social impact, and entrepreneurship.

An early push was the San Francisco Declaration on Research Assessment in 2013. DORA has grown into a worldwide initiative for which reducing the emphasis on journal impact factor has been a "hobbyhorse," says program director Zen Faulkes. "But we are broadening our efforts in assessment reform." As of September, more than 20 000 individuals and about 3000 organizations in 164 countries had signed DORA.

A related effort spearheaded by the European Commission, the European University Association, and Science Europe—an association of funding agencies that spends more than €22 billion (roughly $24 billion) annually—is widely seen as having the most punch. In July 2022 they laid out guiding principles for reform, and in December 2022 they established the Coalition for Advancing Research Assessment (CoARA). More than 600 universities, funders, learned societies, and other organizations, overwhelmingly in Europe, had signed on as of late August. Signatories commit to examining their research assessment procedures within a year and to trying out and reporting on alternative approaches within five years.

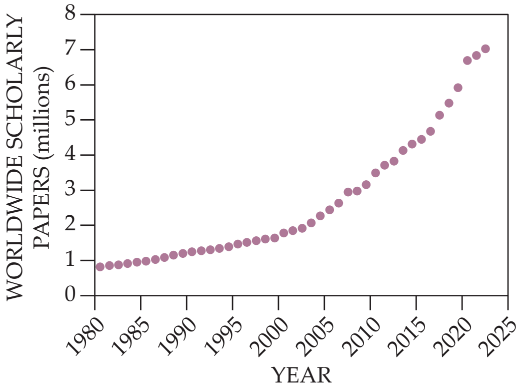
CoARA is different from earlier assessment reform statements, says Sebastian Dahle, a physicist at the University of Ljubljana in Slovenia, a CoARA signatory. "In signing, organizations have to create an action plan. The agreement drives things forward. It's not legally binding, but it keeps people engaged."

KAREN STROOBANTS (on screen), vice chair of the Coalition for Advancing Research Assessment steering board, at the 2023 annual conference of the European Council of Doctoral Candidates and Junior Researchers in Uppsala, Sweden. The council's president, Sebastian Dahle, is seated, third from left. The other panelists represent other organizations that also support reform of research assessment.

The motivation to reform research assessment stems largely from frustration with the publish-or-perish culture that has developed in recent decades, and the movement's aims represent a return to earlier norms. Assessing researchers "almost entirely" on the quantity and citations of their publications "creates poor incentives," says Elizabeth Gadd, vice chair of CoARA's steering board. It leads to scholars "salami slicing" to pad their publication counts, selling authorship, and committing fraud or misconduct, she says, adding that it's "hugely problematic" that publications are so central to evaluating researchers.

In Europe, says Toma Susi, who works on low-dimensional materials at the University of Vienna, "there is a widespread feeling that the academy has lost autonomy in how it evaluates researchers and institutes." The ubiquitous impact factors are commercial and generated in "nontransparent" ways, he says.

Cassidy Sugimoto, chair of the school of public policy at Georgia Tech, studies scientometrics and inequalities in the scientific workforce. She says that the pres-



THE SOARING NUMBER of publications across all fields worldwide reflects the publish-or-perish culture prevalent in academia. It's among the drivers in the movement to reform research assessment. (Adapted from Digital Science, Dimensions software, available from https://app.dimensions.ai/analytics/publication/overview/timeline, accessed on 12 September 2023.)

sure to publish taxes the mental health of scholars. The entire research community is affected, but the burden tends to be higher on women and people of color, she says, in part because on average they are awarded less research funding and their papers are cited less often. If the current system of assessment leads to poorer mental health—and more attrition—she asks, "is it meeting the goals of scientists? Is it best for science?"

Another stress on mental health and a motivation for assessment reform is the frequency of evaluations. Between appraisals, tenure, promotions, prizes, and grant applications, "researchers are evaluated left, right, and center," says Gadd, a specialist on research evaluation, scholarly communications, and research culture at Loughborough University in the UK. "It's a personal driver for me to provide the best environment for researchers to do their research."

Additionally, the open-science movement, which espouses making research—data, methods, software, and more—available to benefit the advancement of both science and society at large, is converging with efforts to reform research assessment. The emphasis on publishing in top journals leads to delays in sharing new discoveries, explains Johan Rooryck, executive director of the international open-access publishing initiative cOAlition S; the 28 funding agencies that belong to the coalition collectively invest about $40 billion a year in research. Around 90% of submissions are rejected by top journals, in many cases without review. "It's impossible that 90% of articles are bad science," he says. Scholars submit their manuscripts repeatedly until they find a journal that accepts them. "It creates enormous waste."

The extreme competition also threatens publishing's peer-review process, says Rooryck, who as an editor-in-chief of the linguistics journal *Glossa* has witnessed firsthand the increasing difficulty of finding reviewers. As a contribution to their research communities, scholars have traditionally volunteered to peer-review papers. But people are practical, Rooryck says. "Without compensation or acknowledgment, why spend time writing reviews?" The system has to change, he says, otherwise it will "come to a screeching halt."

"The way research is conducted has evolved a lot over the past two decades," says Nicolas Walter of the European Science Foundation, which supports CoARA with infrastructure, staff, and financial management. He points to the sheer volume of data and to new ways of generating and sharing data. The outputs of research have also changed, he continues, "so the way we assess research has to evolve." Or, as Susi, who participated in the drafting of the CoARA agreement, puts it, "the bottom line is that qualitative things require qualitative evaluation."

Committing to reform

CoARA sets out four core commitments to guide the reform of research assessment:

► Recognize diversity in the contributions to, and careers in, research.

► Base research assessment primarily on qualitative evaluation, for which peer review is central, supported by responsible use of quantitative indicators.

► Abandon the inappropriate uses in research assessment of journal- and publication-based metrics, in particular the inappropriate uses of journal impact factor and *h*-index.

► Avoid the use of rankings of research organizations in research assessment.

Additional supporting commitments include agreeing to allocate resources, raise awareness, and share results from reform experiments.

CoARA is intended to provide guidance, not prescribe actions. Signatories sign on to the principles, but have to find ways to apply them that work in their specific settings. Research cultures and needs vary by discipline, institution, and country.

This summer, CoARA launched 10 working groups to explore issues relevant to research assessment. Dahle, for example, who is president of the European Council of Doctoral Candidates and Junior Researchers, chairs a working group on early-career researchers. Rooryck chairs one that is looking at how to recognize and reward peer review. Another focuses on multilingualism and language biases in research assessment.

CERN was an early signer of CoARA. CERN's practices and culture already align with CoARA principles, says Alexander Kohls, the lab's group leader for scientific information services. "If you talk to a theorist at CERN, it doesn't matter whether a paper appears in arXiv or a top journal; the content is valued, the venue less so," he says. But, he adds, some CERN collaborators say things along the lines of, "I don't want to make my research output open. I prefer to protect it for my own use." Kohls says that the lab wants "to push forward research assessment reform" in order to nudge other institutions to "follow the spirit" of what CERN has been doing for a long time.

In Poland and other eastern European countries, funding and jobs were historically not based on merit but rather on connections and politics, says Emanuel Kulczycki, head of a research group on scholarly communication at Adam Mickiewicz University in Poznań and an adviser to Poland's ministry of science. A legacy of communism, he says, is that universities remain under government control and the academic community is "eager to trust in metrics." At the same time, he adds, considering social impacts of research is not new there.

In countries with research structures like Poland's, says Kulczycki, reform has to get the nod from the government, "but the black box of evaluation should be designed by the academic community." CoARA could be helpful, he adds, for mining ideas and steps for their implementation. He notes that acknowledging multilingualism is crucial in his country. "Using your own language plays an important role in popularizing science and in attracting students," he says.

Independent of CoARA, in 2020

China instituted reforms along the same lines. Before that, the country had been known for rewarding scholars with cash bonuses for publishing in top international journals. The reforms include valuing a wider range of research outputs and relying on comprehensive peer-review evaluations, says Lin Zhang, a professor of information management at Wuhan University, editor-in-chief of the international journal *Scientometrics*, and an adviser to China's ministry of education on research assessment reform. The earlier incentives improved Chinese researchers' global visibility, she says, "but at a cost of research integrity for some researchers." With new research assessment guidelines, the hope is to focus more on "novelty, scientific value, research quality, research integrity, and societal needs," Zhang says. In reforming research assessment, "China shares the same motivation as the rest of the world."

The US is seen by some as lagging in the area of research assessment reform. That apparent lag can be attributed partly to the decentralized university system and multitude of funding sources, says Sugimoto. And whereas some countries explicitly require, say, a certain number of publications in top-tier journals for someone to get a promotion, in the US such requirements are not typically codified, she notes. "Many of our practices are implicit. That makes them harder to combat."

The European Science Foundation's Walter expects the movement will gain traction in the US and more broadly. CoARA is less than a year old, he notes. "We are now in a phase where we need to engage outside of Europe."

Catalysts, not panaceas

In recent years, a smattering of funding agencies, institutions, and countries have begun experimenting with assessment reforms. Some funding agencies are using lotteries to award grants. Some are putting caps on the number of grants that a given investigator can receive. The Luxembourg National Research Fund (FNR) is broadening the range of contributions for which it awards prizes. As examples, FNR program manager Sean Sapcariu points to a new award that recognizes outstanding mentorship and another that was changed from naming the best publication to rewarding an outstanding research achievement. Funding can be a "blunt tool to shape behavior," he says.

Across Europe, many institutes and funding agencies have begun introducing narrative CVs for job and grant applications; the Netherlands, Norway, and the UK are among the pioneers. For narrative CVs, scholars are asked to limit the number of publications they list to perhaps 5 or 10 and to discuss their relevance. Researchers are also invited to write about other germane contributions and to explain why they are a good candidate for the proposed project or job. "The idea is to provide room for candidates to point out their contributions that may not fit into a traditional CV," says Robbert Hoogstraat, project leader for the Dutch Research Council's Recognition and Rewards program. "Maybe they participated in an open-science activity or wrote an opinion article for a newspaper."

Luxembourg's FNR is both using narrative CVs and studying their efficacy and reception. The FNR asks scientists to produce a two-page CV with three sections: a personal statement related to the research for which they are requesting funding, a description of their professional path, and a discussion of relevant achievements and outputs. So far, says Sapcariu, survey results show that 70% of reviewers and nearly as many researchers view narrative CVs positively. Starting next year, the European Research Council will let applicants add narrative descriptions to their CVs and will give more weight to project proposals than to past achievements.

Capping the number of papers listed in a CV helps level the competition in terms of career stage, gender, and geography, say proponents. Narrative CVs could also make it easier to get funded in interdisciplinary research areas and to switch fields. "The narrative CV is not a panacea," says Frédérique Bordignon, a researcher at the École des Ponts Paris Tech who studies bibliometrics and research integrity. "But it can be a catalyst to find better ways to assess researchers."

Despite funders being uniquely positioned to leverage change, says Angela Bednarek of the Pew Charitable Trusts, they can hit walls. She leads the Transforming Evidence Funders Network, a group of 70 private and public funders that aim to increase the societal impact of their research investments. In response to calls for projects, Bednarek notes, some early-career researchers say, "You are asking me to invest time for something that doesn't get me the publications I need to get tenure."

For example, Bednarek says, a project "might synthesize existing data for use by decision makers," rather than involve pathbreaking research. She points to using data about the physical conditions of the ocean to set fishing limits in response to climate change. "Funders need to think about how research is rewarded and incentivized so they can support relevant and timely research," she says. "We don't call it assessment reform, but it's the same thing."

Metric challenges

A common misinterpretation of CoARA is that proponents aim to do away with metrics. Responsible use of metrics, Bordignon says, should provide context. A statement such as "I have published five articles in the last 10 years and have supervised 10 doctoral students in that period" mitigates the impact of having a single number describe one's work, she says. And since *h*-index grows with the number of publications, indicating academic age would explain the disparity of the *h*-indices between early-stage and seasoned researchers. In addition, metrics used in aggregate can be helpful in comparing the outputs of large institutions or countries.

Among the concerns with reforming assessment are that qualitative assessment may be more time consuming and may be more subjective than relying on metrics. It is harder, proponents admit, especially during a transitionary period as applicants and assessors become familiar with new procedures. But, they say, the increased time required for qualitative assessments could be offset by reducing the total number of evaluations conducted.

DORA's Faulkes says he understands people's concern that "if you take away numbers, it's backroom deals and patronage." But, he says, "We are not saying to abandon metrics entirely." And, Faulkes adds, DORA is joining the "research on research" community to assist in understanding the use of narrative CVs and other qualitative peer-review practices.

"Even coldhearted metrics are not free of biases," says Lynn Kamerlin, a chemistry professor who was involved in science policy in Europe before moving to Georgia Tech last year. Limited jobs and funding are a "zero-sum" game, she says. "Unless the underlying issue of hypercompetition is solved, everything else is a Band-Aid."

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The Department of Physics and the Department of Chemistry and Biochemistry at the University of Oregon invite applications for a **Materials Science faculty position** to start Fall 2024. Applicants should have a PhD and an outstanding research record. The successful candidate will be expected to build a world-class research program, teach graduate and undergraduate courses with distinction, and perform university service and public outreach. The University of Oregon champions diversity, and strongly encourages applications from women and other individuals identifying as BIPOC, LGBTQIA+, neurodivergent, disabled, and persons of marginalized gender.

To apply, please complete the online application; including cover letter, curriculum vitae, statement of research plans and objectives, statement on teaching philosophy or interest, statement outlining past/current efforts and plans for advancing diversity, equity, and inclusion, and names and contact information for three professional references, who may be contacted to provide letters of recommendation.

Application Link:
careers.uoregon.edu/en-us/job/532150/assistant-professor-of-chemistry-biochemistry-or-physics

ABIGAIL MALATE

Eugenia Etkina is an emerita distinguished professor of science education at Rutgers University in New Brunswick, New Jersey. She is the codeveloper of the Investigative Science Learning Environment approach to introductory physics.

WHEN LEARNING PHYSICS MIRRORS DOING PHYSICS

Eugenia Etkina

The Investigative Science Learning Environment approach replaces traditional teaching with active-learning methods that emulate scientific processes.

Many years ago, Andrew, one of the best students in my introductory physics course, said to me, "I know how to get a good grade in physics, but I feel like what we do in class can't be what physicists do when they do physics. I wonder what they actually do." That comment got me thinking: Is it possible for a student to experience real physics while learning it? Is it important when you are taking an introductory physics course to know and feel like you are doing what physicists do?

After almost 40 years of grappling with Andrew's comment, I think the answer to both questions is yes. With proper pedagogy, students can experience real physics, and they can benefit tremendously from feeling like actual scientists. As a result, I've helped develop the Investigative Science Learning Environment (ISLE) approach to learning and teaching physics.[1] Below I introduce it and demonstrate how it both deals with Andrew's concerns and addresses what I believe are the major challenges facing physics education in the 21st century.

ISLE in action

Imagine an introductory physics course for physics or science majors. The students have already learned about Newton's laws, momentum and energy, and mechanical waves, and they are now studying geometrical optics. They've learned how to draw ray diagrams and explain shadows, and they are familiar with the law of specular reflection. In the previous class, they used Newton's particle model to explain the relationship between angles of incidence, angles of reflection, and shadows.

In their first encounter with refraction, students in a lab section are split into groups of three or four and tasked with designing an experiment to investigate what happens when a laser beam hits the flat surface of a semicircular piece of plexiglass. Their goal is to find a pattern in the paths of the incident ray and the ray that passes through the plexiglass.

They set up an experiment (see figure 1) and measure the angles with respect to the normal line from the incident surface. The lab handout provides them with hints on how to find a pattern in the data by using trigonometric functions. They do their work on small whiteboards and share their findings with the rest of the class. Some of the groups come up with Snell's law.

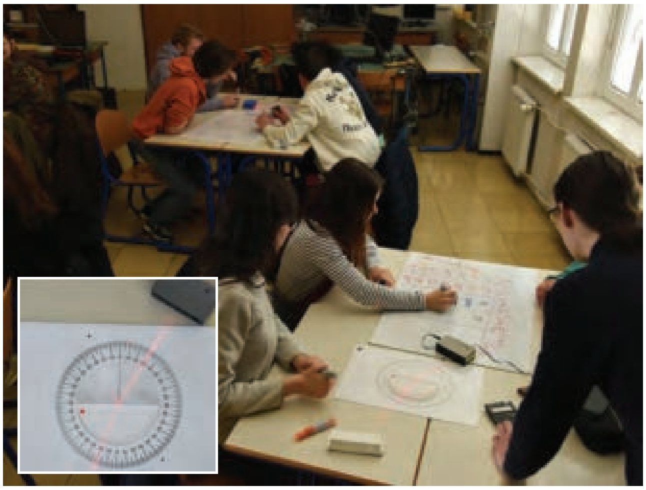

FIGURE 1. STUDENTS LOOK FOR A PATTERN in the paths of incident and refracted light beams. The whiteboard and experiment are both visible on the tables. The inset shows a top-down view of the laser beam hitting the plexiglass.

The class's next task is to use the particle model of light to explain why the light's path changed in the way it did. After a class discussion and prompts from the instructor, the students come up with the following idea: The surface of the plexiglass slab exerts an attractive force on light particles, which causes the component of velocity along the normal line to increase. Because the velocity component that is parallel to the plexiglass surface does not change, the beam bends toward the normal line (see figure 2).

If that explanation is correct, the speed of light in plastic should be greater than it is in air. To test that hypothesis, students need to design an experiment that measures the speed of light in plexiglass. The instructor shows them a new device: a laser distance meter used in construction to measure distances.[2] Playing with the device, students learn how it determines distance to an object: It uses the value for the speed of light in air to measure the time delay between the emitted and received pulses.

The students design the following experiment: They place the distance meter so that the laser beam passes through the plexiglass slab and reflects off a surface at the slab's end. They record the distance measured by the device. Then they let the beam follow the same distance through the air. If their hypothesis is correct, the distance the beam travels through the plexiglass should be shorter than the distance through the air. They run the experiment and find that the device measures a longer distance in plexiglass (see figure 3). It looks like light travels slower in plexiglass than in air, which means that the particle-based explanation of refraction is not correct.

Is there another way to explain how the beam of light changes direction in the plexiglass? One student suggests that light might behave like a wave. Back in their groups, the students use their knowledge of mechanical waves and Huygens's principle to explain how a wave model of light can account for the outcome of the initial refraction experiment (see figure 4). In the follow-up class, they review their wave model and continue learning the properties of light.

As you can see, ISLE is very different from traditional pedagogy. Instead of sitting through a lecture—or reading a textbook—about the wave model of light and how it explains refraction, students not only come up with the idea themselves but also learn why the particle model of light does not explain the phenomenon. As they progress through the process, they learn how to design experiments to find qualitative and quantitative patterns in new phenomena, devise hypotheses explaining those phenomena, design experiments to test their hypotheses, use different graphical representations to analyze the phenomena, make predictions about the outcomes of further experiments, rule out hypotheses based on those experimental results, work with their group, and present their findings and procedures to the whole class.[1]

In the ISLE approach, experimental work is an integral part in the development of students' physics knowledge rather than an add-on in which they simply test models presented in lectures. Interconnecting the experimental and theoretical development of models mirrors the process used by physicists to construct knowledge and engages introductory students in authentic physics while they are learning new ideas. Students experience what physicists do when they do physics. That is what Andrew was looking for.

How and what should students learn?

But is that experience important? Class time is brief, and many instructors feel pressure to cover lots of material in a course. If they spend too much time letting students figure out stuff on their own, they might not be able to cover all the material. But the field of physics has imposed that pressure on itself to cover all that information. Thousands of students take introductory physics courses in the US and across the world. Some will become physicists, and for them the experiential part of learning

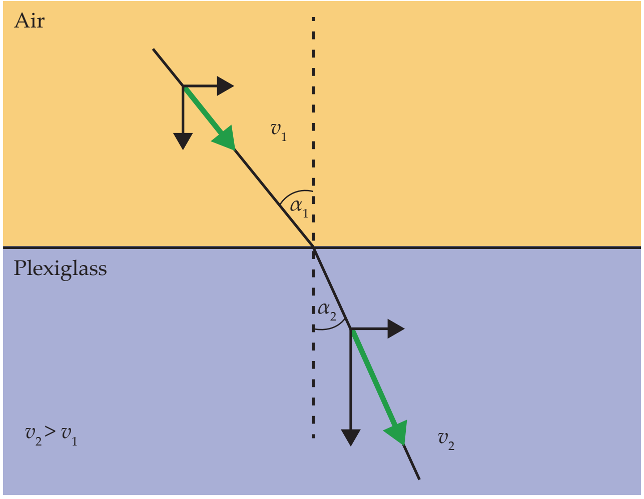

FIGURE 2. EXPLAINING REFRACTION with the particle model of light. Traveling at velocity v_1 in air, a light particle enters a plexiglass slab at an angle of incidence α_1. As the light enters the plexiglass, it refracts at an angle α_2 that is smaller than α_1. To explain that bending using the particle model of light, students hypothesize that when the light particle crosses the air–plexiglass boundary, the glass exerts an attractive force on the particle that causes an increase in the component of velocity perpendicular to the boundary. As a result, the light velocity v_2 in the plexiglass will be faster than the light velocity v_1 in air.

physics through the ISLE approach will be a window into their future profession.

But many will become doctors, ecologists, chemists, politicians, journalists, pharmacists, biologists, and so on. What do those students need to learn in introductory physics courses to be prepared for success in their field in the 21st century? What will they need to remember from their physics course 3, 5, or 10 years down the road? Although some knowledge of physics content might be useful for a pediatrician trying to help a feverish child, they will certainly need to collect data, identify patterns, come up with an explanation for the symptoms, and predict what kind of treatment is appropriate.

The question of what students should learn in our courses is especially timely now that artificial intelligence is becoming increasingly successful at solving traditional physics problems and answering conceptual questions. International agencies debating college educational priorities,[3] domestic organizations like the National Research Council that set goals for K–12 science education,[4] and prominent physicists interested in pedagogy have all looked into the question, and they send the same message: Students need broad and specialized knowledge. Moreover, as a recent report by the Organisation for Economic Co-operation and Development states, "knowledge about the disciplines, such as knowing how to think like a mathematician, historian or scientist, will also be significant, enabling students to extend their disciplinary knowledge" (reference 3, page 5).

In an article in Physics Today (September 2022, page 46), Carl Wieman gives examples of decisions that physics students need to learn how to make so they can think like physicists. The lackluster responses to the COVID-19 pandemic and the

Examples of ISLE problems

Several categories of problems are available in the Investigative Science Learning Environment (ISLE) curriculum resources. Here are example problems for two categories. More can be found in references 1 and 15.

Category: Evaluate reasoning or solution. Students must critically evaluate the reasoning of imaginary people or a suggested solution to the problem, which is given in words, graphs, diagrams, or equations. Students must recognize productive ideas, even when they are embedded in incorrect answers, and differentiate them from unproductive ideas.

Example 1. You are given a loop raceway for Hot Wheels cars. While playing with the cars, you and your friends notice that you need to release a car from a minimum height H of at least 1.3 diameters of the loop above the ground to prevent the car from falling off the track at the top of the loop. Two of your friends have different explanations for the observed pattern. Leila argues that the minimum height H must be larger than the loop diameter d, even if the friction forces are negligible, because otherwise the car would fall off the loop at the top. Jordan, on the other hand, insists that if there were no friction forces exerted on the car, the minimum height H would be equal to the loop diameter d because the mechanical energy of the car–Earth system is constant.

Analyze each explanation and describe what physics ideas Leila and Jordan used to arrive at their answer, even if you think their answer is incorrect. Then decide which of them is correct. Explain how you made your choice.

Example 2. Some students are given the following problem: "A 5000 cm^3 cylinder is filled with nitrogen gas at 1.0×10^5 Pa and 300 K and closed with a movable piston. The gas is slowly compressed at constant temperature to a final volume of 5 cm^3. Determine the final pressure of the gas." (a) Explain, with quantitative arguments, why the ideal-gas law cannot be applied to solve this problem. (b) Modify the problem so that it can be solved using the ideal-gas law and give your solution.

Category: Design an experiment or pose a problem. Students must design an experiment, an experimental procedure, or a device that will allow them to measure or determine certain physical quantities or that would meet specific requirements.

Example 1. To develop a touch detector, you connect two force sensors to a computer and a meter stick of known mass. The sensors are used to keep the stick horizontal. (a) How can you use that setup to design an experiment that uses the readings of the two force sensors to determine the magnitude of any pushing force F and the location of its application on the stick x? (b) How can you use that setup to derive an expression that can be used as a computer algorithm to calculate x and F using the readings of the force sensors and the parameters?

Example 2. Design two experiments, using different methods, to determine the mass of a ruler. Your available materials are the ruler, a spring, and a set of three objects, one with a standard mass of 50 g, one of 100 g, and one of 200 g. One of the methods should involve your knowledge of static equilibrium. After you design and perform the experiments, decide whether the two methods give you the same or different results.

Designing and conducting an observational experiment				
Scientific ability	Missing	Inadequate	Needs improvement	Adequate
Designing a reliable experiment that investigates the phenomenon.	The experiment does not investigate the phenomenon.	The experiment may not yield any interesting patterns.	Some important aspects of the phenomenon will not be observable.	The experiment yields interesting patterns relevant to the investigation of the phenomenon.
Identifying a pattern in the data.	No attempt is made to search for a pattern.	The pattern described is irrelevant or inconsistent with the data.	The pattern has minor errors or omissions, or terms aren't properly defined.	The pattern represents the relevant trend in the data. If possible, the trend is described in words.
If applicable, representing a pattern mathematically.	No attempt is made to represent a pattern mathematically.	The mathematical expression does not represent the trend.	No analysis of how well the mathematical expression agrees with the data is included, or some features of the pattern are not represented in the expression.	The mathematical expression fully represents the trend, and an analysis of how well it agrees with the data is included.

A SELECTION OF RUBRIC CRITERIA used by students to assess themselves when they design and perform observational experiments. The same criteria are also used by instructors to provide feedback.

ongoing climate crisis make it clear that physics educators have not paid enough attention to teaching students those thinking skills. Understanding the nature of scientific knowledge is an essential part of a liberal arts education. Our physics students need to learn how to think like physicists even if they are not planning to enter the field after graduating.

How can students learn physics concepts and models while also learning to think like a physicist? In the past 30 years, the educational community has established that interactive engagement methods lead to better student learning gains than traditional methods.[5] As brain studies have shown, learning involves physical changes in a person's brain and body.[6]

In other words, it is impossible to transmit knowledge by lecturing: The learner must construct it themselves by actively participating in the instructional process and thereby altering their brain connections. But for that to happen, the learner needs to be motivated and feel that they are capable of learning. Although our students have been doing physics all their lives by living and navigating in the physical world, many of them feel that physics is a foreign subject that is detached from their lives. Over the past 20 years, researchers have accumulated evidence that after students take a physics course, their attitudes toward physics and perception of their ability to do physics decline.[7]

Pedagogical challenges

I believe physics educators face three challenges. The first is shifting the focus of learning from the pure outcomes of physics as an intellectual endeavor to the process through which those outcomes are obtained. In other words, instructors need to help students learn by experiencing how physicists construct knowledge. The second is changing the focus of physics pedagogy from simply transmitting physics knowledge to students to creating an environment in which they can self-construct that knowledge. The third is helping students believe that they can do physics and that they belong in physics—

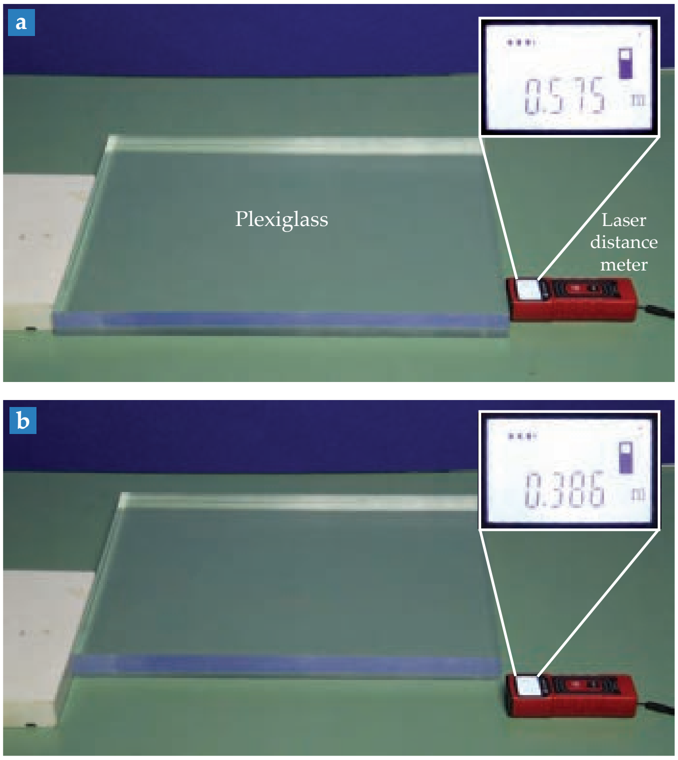

FIGURE 3. IN AN EXPERIMENT, Investigative Science Learning Environment students use a laser distance meter (lower right corner of each panel, with insets of the readouts) to measure the distance traveled by light **(a)** in plexiglass and **(b)** in air. They then compare those speed-of-light measurements to determine in which one light travels faster.

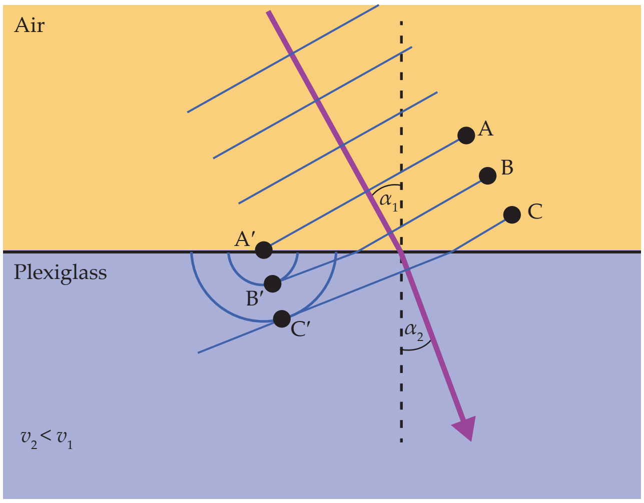

FIGURE 4. EXPLAINING REFRACTION with the wave model of light. Traveling at velocity v_1 in air, a light wave enters a plexiglass slab at an angle of incidence α_1. As it enters the plexiglass, the light refracts at an angle α_2 that is smaller than α_1. To explain that bending using the wave model of light, students hypothesize that once the points on a wavefront reach the air–plexiglass boundary, the radii of the circular wavelets that emerge from those points in plexiglass—according to Huygens's principle—will be smaller than in air. The progression of wavefronts from A–A′ to C–C′ shows how they bend. That can happen only if the light velocity v_2 in the plexiglass is slower than the light velocity v_1 in air.

namely, helping them see themselves as physicists even though they may take different career paths.

The ISLE approach is only one of many pedagogical tools with interactive engagement methods developed by the physics-education research community over the past 30 years. Others include the SCALE-UP (Student-Centered Active Learning Environment for Undergraduate Programs) project,[8] the physics tutorials pioneered at the University of Washington,[9] peer instruction,[10] paradigms,[11] and modeling instruction.[12] Studies show that they all are more effective at helping students learn physics than transmission modes of instruction.

Although all those approaches have students working in groups to produce answers to the questions posed by the materials developers, only two of them—modeling instruction and ISLE—have students constructing their knowledge through a process based on how physicists do it. And only the ISLE process teaches students to explicitly generate and test alternative hypotheses to explain a phenomenon. It also provides rubrics to help students self-assess and improve their work. My example at the beginning of this article represents the logical flow through which the students construct concepts and relations in an ISLE classroom[1] (see figure 5).

In a typical ISLE class, students work in groups to observe physical phenomena, identify patterns, and devise multiple explanations or hypotheses—qualitative or quantitative—without knowing which one is correct. They use analogical reasoning, graphical representations, and mathematical tools; share their findings with the rest of the class; and come up with a consensus on what hypotheses should be tested experimentally. They then design experiments to test those hypotheses. Before conducting an experiment, they make predictions about its outcome. They compare the results with their predictions and decide which hypotheses they can reject. That process repeats as many times as needed until only one hypothesis is left, which students then apply to solve sample problems. At the end, the instructor summarizes what students have found and shares accepted physics material related to students' findings.

The continuous interplay between the physical world and models is central to the way that physicists generate new knowledge. Research suggests that the ISLE approach to teaching and learning physics is representative of how physicists work. A recent study by the physics-education research group at the University of Washington, for example, observed that experts—both faculty members and graduate students—develop and test hypotheses in a cyclical manner when they model a novel paper-and-pencil problem. We observed similar cycles when faculty are presented with novel experimental problems.[13]

Although the ISLE process may seem long and complicated, it does not take much time and can be easily implemented during a typical class as long as students are familiar with it. More than 20 years ago, our development team at Rutgers University, in an effort to help students engage in the ISLE approach effectively, came up with a list of scientific abilities that represent the processes and activities used by physics practitioners. Each ability was broken down into several smaller subabilities that match many of the decision-making steps physicists undertake that Wieman mentioned in his 2022 Physics Today article. We then devised a set of activities that help students develop those abilities.[14]

We have also developed descriptive rubrics for each subability to help students self-assess and improve their work and to guide instructors in providing feedback to students.[14] The table on the previous page provides several rubric examples that students use when they design an experiment to observe a phenomenon and find patterns. Over the years we have developed a library of curriculum resources for introductory physics courses[1] and a textbook that is designed to accompany a class taught with ISLE pedagogy.[15] Finally, we have developed a library of nontraditional real-life problems that do not have one right solution and that engage students in the decision-making processes identified by Wieman. The box on page 29 illustrates a few examples of such problems, which help students develop traditional problem-solving skills while also teaching them how to think like physicists.

ISLE and belonging

But how does the ISLE approach help address the third challenge I discussed—namely, helping students believe that they can both do and belong in physics? It does so in four ways. First, when students are beginning to learn a new idea and are observing initial experiments, they are not asked to predict the outcome but to say in simple words what they observed. That step removes the feeling of failure that often exists when students are obliged to make a prediction about something they know little to nothing about and quickly see that it is wrong. If students are asked to observe experiments, they all start on the same page, are ultimately successful, and feel that they can do it. As the students work together on the activities, they gain expertise as a community, which makes every student feel that their contributions are valued and that they belong.

Second, when students develop their own hypotheses—we call them wild ideas—to explain the outcomes of observational experiments, those hypotheses do not need to be correct, but they need to be testable. As students work in groups, they share their designs and make predictions based on their wild ideas. If the outcomes of their experiments don't match the predictions, their personal intuition hasn't failed—the wild idea has. So no harm is done to their self-confidence: On the contrary, they often feel that they have accomplished something that is very valuable in science—they ruled out a possible hypothesis! That's not an experience that most physics students get to have. It teaches them that knowing the right answer is not nearly as important as creativity and persistence.

Third, the ISLE approach consistently asks students to use graphical representations as a bridge between words (or physical phenomena) and algebra (or calculus), which helps individuals who need concrete imagery to describe a process with mathematical symbols. But it's not only students who have trouble with math who benefit from the multiple-representation approach. Recent research in cognitive science shows that it helps all learners. Understanding the interplay between representations is a hallmark of advanced physics thinking, which means that ISLE helps all students reason more like experts and increases their potential for belongingness in physics.

Finally, the ISLE course structure encourages students to resubmit improved lab reports, homework, quizzes, and even exams for a better grade, which helps them feel that their learning is valued. Students thus get accustomed to understanding that they might not succeed on the first try, but if they persevere, they can make it in physics.

In my Millikan Medal (now the McDermott Medal) lecture at the 2014 American Association of Physics Teachers Summer Meeting, I gave an overview of the literature on student experiences in introductory physics courses taught with the ISLE approach.[16] As I described, ISLE students show high learning gains in conceptual understanding, approach problem-solving in an expert-like manner, and develop physical reasoning and experimental abilities that help them when they learn new material. Another recent study shows that ISLE students feel that they can succeed in physics and that what they are learning in ISLE courses is useful for their studies in other classes, for their future in the workplace, and in their lives in general.[17]

Why use the ISLE approach?

Because the ISLE process alters the environment in which students learn physics to better help them succeed, it conforms to what the architect Ronald Mace called universal design: the adaptation of an environment to be accessible by everyone, regardless of their age or ability. It is not surprising that the disability expert Julie Maybee recently argued that the ISLE approach is an example of universal design for physics education.[18]

Evidence shows that the ISLE approach is inclusive[17] and helps students learn.[16] If that doesn't convince you, I encourage you to ask yourself the same question I asked myself: After the dust settles, how do you want your students to be transformed by your teaching? If you'd like them to think more like a physicist and carry those skills with them throughout their lives—regardless of what they do—then I encourage you to consider ISLE.

At the beginning of the COVID-19 pandemic, I created a Facebook group called "Exploring and applying physics" for those who want to implement our approach. In the forum, we post curriculum materials, encourage everyday professional development, run monthly workshops, and discuss student learning and current research. Today the group has more than 2200 members from every continent except Antarctica. You are welcome to join our community!

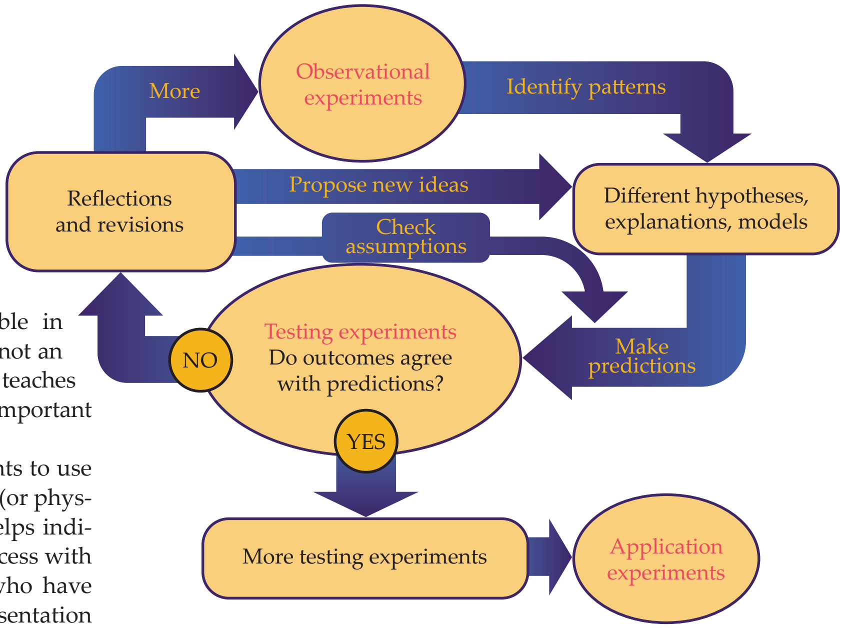

FIGURE 5. A SCHEMATIC MODEL of learning activities employed in the Investigative Science Learning Environment approach.

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RICE

FACULTY POSITIONS IN EXPERIMENTAL AND THEORETICAL QUANTUM SCIENCE

The Department of Physics and Astronomy at Rice University in Houston, Texas invites applications for **two tenure-track faculty positions**, one experimental and one theoretical, in the area of quantum science using atomic, molecular, or optical methods. This encompasses quantum information processing, quantum sensing, quantum networks, quantum transduction, quantum many-body physics, and quantum simulation conducted on a variety of platforms. The ideal candidates will intellectually connect AMO physics to topics in condensed matter and quantum information theory. In both searches, we seek outstanding scientists whose research will complement and extend existing quantum activities within the Department and across the University. In addition to developing an independent and vigorous research program, the successful applicants will be expected to teach, on average, one undergraduate or graduate course each semester, and contribute to the service missions of the Department and University. The Department anticipates making the appointments at the assistant professor level. A Ph.D. in physics or related field is required by June 30, 2024.

Applications for these positions must be submitted electronically at **apply.interfolio.com/131378** (experimental) and **apply.interfolio.com/131379** (theoretical). Applicants will be required to submit the following: (1) cover letter; (2) curriculum vitae; (3) statement of research; (4) statement on teaching; (5) statement on diversity, mentoring, and outreach; (6) PDF copies of up to three publications; and (7) the names, affiliations, and email addresses of three professional references. Rice University, and the Department of Physics and Astronomy, are strongly committed to a culturally diverse intellectual community. In this spirit, we particularly welcome applications from all genders and members of historically underrepresented groups who exemplify diverse cultural experiences and who are especially qualified to mentor and advise all members of our diverse student population. We will begin reviewing applications by November 15, 2023. **To receive full consideration, all application materials must be received by December 15, 2023. The expected appointment date is July 2024.**

Assistant Professor of Physics

Atomic, Molecular, and Optical

The Department of Physics at the University of Wisconsin–Madison invites applications for a tenure-track faculty position in the area of experimental AMO physics. The Department of Physics has a strong experimental AMO physics group with experiments on quantum manipulations of neutral atoms, quantum sensors, and quantum optics, plus closely related theoretical and experimental efforts in quantum devices including quantum dots and superconductors.

The successful candidate will have the opportunity to collaborate with existing quantum and AMO research at UW–Madison, within the Wisconsin Quantum Institute (WQI) and the HQAN and Q-NEXT quantum centers, and with external research centers. The candidate will be expected to teach at all levels, conduct high-impact scholarly research, and provide service to the department, college, university and academic community nationally or internationally. A Ph.D. in physics and one year postdoctoral experience with AMO specialization is required prior to the appointment start date.

To ensure full consideration, apply by December 4, 2023. Visit go.wisc.edu/AMOfaculty

WISCONSIN
UNIVERSITY OF WISCONSIN–MADISON

Washington University in St. Louis

The Department of Physics at Washington University in St. Louis invites applications for the Edwin Thompson Jaynes Fellowship. We welcome applicants with interests in the research areas of the Department of Physics (Nuclear and Particle Physics, Condensed Matter Physics, Quantum Information, Biophysics, and Astrophysics and Cosmology). The Fellowship is a prize fellowship managed by the Department of Physics. Successful candidates are expected to propose a tentative research program, and further develop and refine that program during their fellowship at Washington University in St. Louis. The aim of the fellowship is to prepare candidate(s) for faculty positions at research institutions or staff scientist positions at national laboratories. Awardees will pursue an independent research program, collaborating with one or several faculty members from the Department of Physics. Jaynes Fellows will be initially appointed as postdoctoral fellows and are anticipated to continue for three years.

Please visit **https://physics.wustl.edu/jaynes-fellowship** for more information, or apply directly at **https://apply.interfolio.com/129807** by November 15, 2023. For inquiries about the fellowship please contact **jaynes_fellowship@physics.wustl.edu**.

Physics and Astronomy
University of Missouri

George H. Vineyard

ASSISTANT PROFESSORSHIP OF THEORETICAL CONDENSED-MATTER PHYSICS

The Department of Physics and Astronomy at the University of Missouri-Columbia invites applications for a named faculty position in theoretical condensed-matter physics at the tenure-track Assistant Professor level, beginning on August 1, 2024. The position is supported by the George H. Vineyard endowment fund.

We seek candidates who will establish a vigorous, externally funded research program at the forefront of condensed-matter theory. Research areas may include, but are not limited to, topological phases of matter, strongly correlated electronic and magnetic materials, spintronics, quantum information, and computational materials science. We are particularly interested in applicants whose research complements the department's existing strengths in condensed-matter theory and experiment. Our condensed-matter program benefits from, and has strong connections to, a number of important campus resources, including the MU Materials Science and Engineering Institute (MUMSEI), a new state-of-the-art Electron Microscopy Advanced Technology Core, and the MU Research Reactor (MURR).

A Ph.D. in physics by time of appointment is required.

To apply, please visit: **https://hr.missouri.edu/job-openings** (Job Opening ID 48339). Merge your CV with a brief cover letter and upload the document in the Resume/CV section of the application. Applications should also include a statement of research and teaching interests along with the names and contact information of three references. For further inquiries regarding the position, please contact Professor Carsten A. Ullrich at **ullrichc@missouri.edu**. Contact Human Resource Services (**muhrs@missouri.edu**) for any questions about the application process.

Review of applications will begin on December 1, 2023, and will continue until the position is filled.

We value the uniqueness of every individual and strive to ensure each person's success. Contributions from individuals with diverse backgrounds, experiences and perspectives promote intellectual pluralism and enable us to achieve the excellence that we seek in learning, research and engagement. This commitment makes our university a better place to work, learn and innovate. In your application materials, please discuss your experiences and expertise that support these values and enrich our missions of teaching, research and engagement.

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The **INL Distinguished Postdoctoral Associate Program** is designed to attract, recruit, develop and inspire early-career researchers who have the potential to develop into INL's future scientific and technical leaders. These appointments are highly competitive and intended to recognize and provide Distinguished Postdoc Associates with a competitive award, research experience, mentorship, and training to develop their capabilities. All the appointments are in person at our Idaho Falls complex and site facilities.

INL's Distinguished Postdoctoral Program Opportunity:

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- Access to cutting-edge instrumentation and facilities
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Russell L. Heath Distinguished Postdoctoral Research Associate Appointment

Idaho National Laboratory has postdoctoral research positions available through its Russell L. Heath Distinguished Postdoctoral Research Associate program. The distinguished appointment is awarded to early-career scientists and engineers interested in advancing the fields of nuclear energy, critical infrastructure protection and clean energy. Outstanding applicants with research interests over a broad range of fields supporting INL's mission including, but not limited to, chemistry; physics; materials science; nuclear, mechanical and electrical engineering; earth/environmental science; separations science; biomass; geology; catalysis; advanced manufacturing; computational science; cybersecurity; electric vehicles and infrastructure; battery technologies; power engineering; wireless technology; systems analysis and design; or any related field are encouraged to apply. This appointment provides up to two years of research support with a possible one-year extension.

Deslonde De Boisblanc Distinguished Postdoctoral Appointment

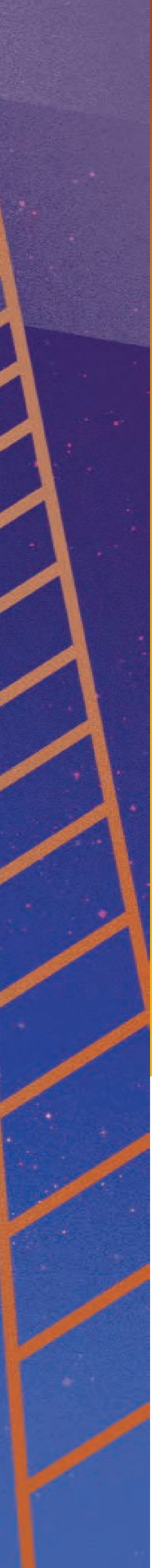
This appointment will be awarded to early-career nuclear scientists and engineers to perform leading research and development for advanced reactor design and development as well as support operations, safety, fuel management, experiment management and other pertinent activities associated with INL research reactor facilities (e.g., the Advanced Test Reactor, used to support advanced reactor development). Outstanding applicants will have in-depth knowledge of computational and experimental reactor physics, core design optimization, nuclear instrumentation and thermal fluids science, and experience with established and well-validated reactor analysis tools such as, but not limited to, RELAP, MCNP, HELIOS, SCALE and Serpent. This appointment provides up to two years of research support with a possible one-year extension.

Apply Today! Scan the QR code for more information or to apply online.

Applications will be accepted from Sept. 1, 2023, through Dec. 31, 2023, for positions starting in the 2024/2025 timeframe, although earlier appointments are possible. Notification of decision will be made within four months of receiving the application package. Applications should include a current CV, unofficial transcripts, a letter of interest including long-term professional goals, abstract of the doctoral dissertation, three letters of recommendation (one must be from a Ph.D. advisor), one peer-reviewed publication re/preprint, and a short research proposal.

Minimum qualifications include a doctorate degree in a field applicable to nuclear science and engineering research completed within the last five years; favorable recommendations; and demonstrated leadership, written and oral communication skills, and ability to work independently and as part of a team.

ABIGAIL MALATE



Rachel Ivie is a senior research fellow at the American Institute of Physics in College Park, Maryland. **Susan White** directs AIP's Statistical Research Center.


WHEN YOUR ACADEMIC LADDER IS LONGER

Rachel Ivie and Susan White

Race and ethnicity can affect how quickly a faculty member receives tenure.

For those working in academia, the tenure process is one of the last hurdles in what has been a long series of obstacles and challenges. On the face of it, the process seems straightforward: The candidates' scholarly work is reviewed by their peers, and tenure is awarded based on the merits of the work. Of course, such statements greatly oversimplify the process and overlook the influences on the process that are outside the candidates' control.

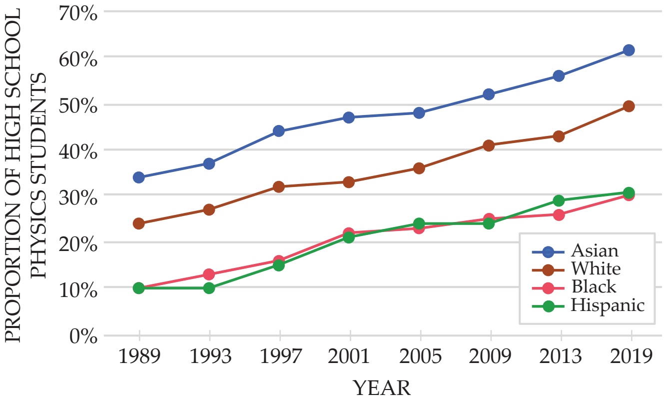


FIGURE 1. THE PROPORTION OF STUDENTS in different racial and ethnic groups that have taken high school physics in the US. (Adapted from ref. 11.)

Some influences that contribute to differences in tenure outcomes include whether the faculty member took a postdoc and whether the faculty member earned a degree outside the US. They can also include demographic characteristics, such as gender, race, and ethnicity. Another factor is whether a faculty member asks for and is granted more time until their tenure review, commonly known as stopping the tenure clock.[1]

Barriers experienced by faculty members who are women and who are from other minoritized groups have been documented clearly in the literature. Faculty members who are Black encounter biased teaching evaluations, inequitably distributed resources, lower salaries, and unwelcoming environments—in addition, university leaders often undervalue their service work.[2,3] Latino faculty members must negotiate workplaces with difficult climates that create isolation and alienation.[4] Faculty members who are Asian or Asian American face stereotypes that limit their advancement in academe.[5] Women faculty members must deal with less access to resources, isolation,[6] and sexual harassment.[7] All the barriers create cumulative disadvantage, a situation in which those who are minoritized receive fewer resources than their advantaged colleagues,[8] which ultimately leads to a gap in career progress and recognition between white men and people from minoritized groups, including women.

Research, especially qualitative research, shows that the experiences of members of minoritized groups are multidimensional, complex, and unable to be explained neatly. No one person's experiences are exactly like another's. But the overwhelming conclusion is that the experiences of faculty members from minoritized groups differ significantly from those of faculty who are white and who are male—and often are much less positive.

Our analysis in this article attempts to document one result of the cumulative disadvantage caused by those multiple barriers. In this article, we use data from a 2021 survey of physics and astronomy faculty members conducted by the American Institute of Physics (the publisher of Physics Today) to describe how gender, race, and ethnicity affect the length of time between receiving a PhD and receiving tenure for faculty members in physics and astronomy departments.

Diversity in physics

It has been long recognized that members of minoritized racial and ethnic groups are poorly represented in physics relative to their representation in US society. The situation is similar in astronomy,[9] and other reports have documented the lack of representation of women in physics and astronomy.[10]

The underrepresentation of people who are Black/African American and Hispanic/Latino in physics starts early on the academic pathway. (In discussing results of the 2021 survey, we use the terms that were presented to the respondents on the questionnaires.) Figure 1 shows that Hispanic/Latino students and Black/African American students are less likely to take physics in high school than white students and Asian/Asian American students. Those differences are largely a function of the socioeconomic status of the high school the students attend, because Black/African American and Hispanic/Latino students are less likely to attend a school that offers physics.[11]

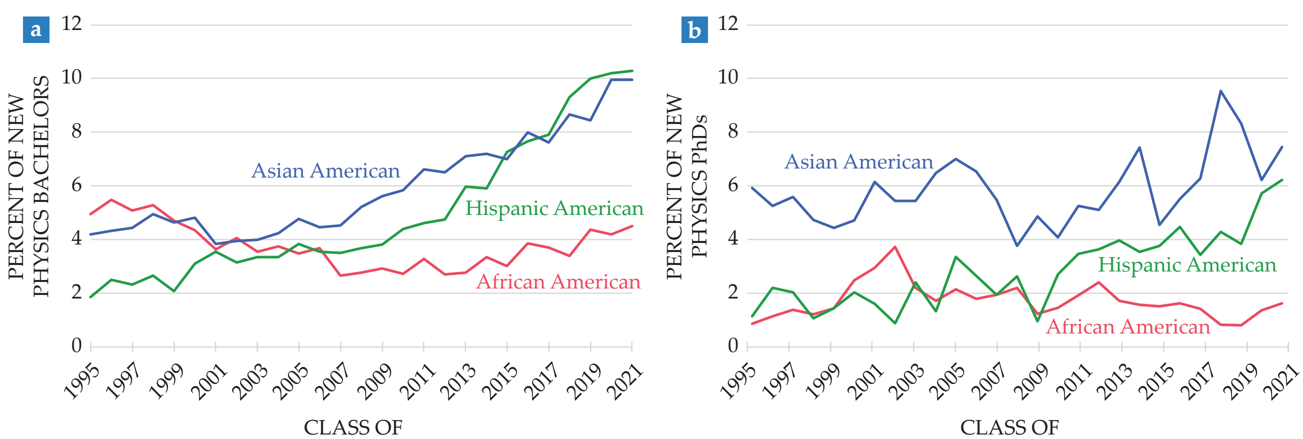


FIGURE 2. UNDERREPRESENTATION IN PHYSICS. (a) For the class of 2021, Black/African American students earned just 4% of physics bachelor's degrees, and Hispanic/Latino students earned about 10% of physics bachelor's degrees. But the approximate representation of people from those two groups in the US population is 14% and 19%, respectively.[12] **(b)** People from the two groups are also underrepresented among physics PhD graduates. In 2021, less than 2% of PhD graduates were Black/African American, and 6% were Hispanic/Latino. (Courtesy of the American Institute of Physics Statistical Research Center.)

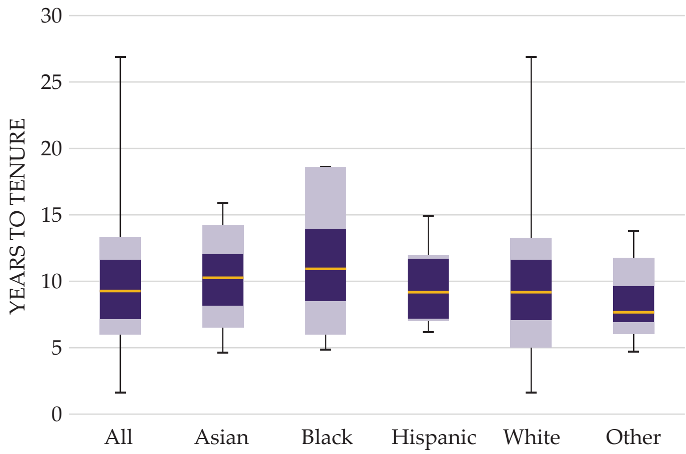


FIGURE 3. FACULTY MEMBERS who are Asian/Asian American and Black/African American have longer median times to tenure than faculty members who are white. The data come from a 2021 faculty survey administered by the American Institute of Physics. The dark purple boxes indicate the middle 50% of the data, and the median is indicated by the yellow lines. The light purple boxes extend to the 10th and 90th percentiles.

Figure 2 further illustrates the continued underrepresentation of people who are Hispanic/Latino and Black/African American at higher levels in the physics educational system. For the class of 2021, Black/African American students earned just 4% of physics bachelor's degrees, and Hispanic/Latino students earned about 10% of physics bachelor's degrees. But the approximate representation of people from those two groups in the US population is 14% and 19%, respectively.[12] People from the two groups are also underrepresented among physics PhD graduates. In 2021, less than 2% of PhD graduates were Black/African American, and 6% were Hispanic/Latino. At the faculty level, most people in physics and astronomy departments identified as white. In 2021, about 7% identified as Asian/Asian American, 2% as Black/African American, and 4% as Hispanic/Latino. Among tenured faculty members, the numbers were 8%, 2%, and 4%, respectively.

Members of minoritized racial and ethnic groups are poorly represented in physics.

Although the representation of Asian/Asian American people in physics is low, it is not lower than their representation in the US population, which is 6.3%. For that reason, Asian/Asian American people are not considered underrepresented in physics. But a group's representation compared with the general population says nothing about whether people in that group experience inequality in their educational or professional careers. To document one aspect of that inequality, we analyzed whether faculty members who are Asian/Asian American, Black/African American, or Hispanic/Latino take longer on average to receive tenure than white faculty members.

Faculty survey

In the spring semester of 2021, we sent a questionnaire to a representative sample of approximately 5500 faculty members in US degree-granting physics and astronomy departments. The approximately 1800 respondents included adjuncts and faculty members who were tenured, not yet tenured, and not on the tenure track.

Our goal was to focus on early-career academics. Because some faculty members may have entered academia after a career working in another sector—and it likely took those people longer to earn tenure—we removed from our analysis faculty members who took more than 10 years to become an assistant professor after earning their highest degree. We found no statistically significant difference in race and ethnicity or in gender between those who took more than 10 years to reach assistant professor and those who did not.

In our analyses, we include 448 respondents who had received tenure and used the data in an ordinary least-squares regression model.[13] On the basis of the literature, we hypothesized that faculty members who are women[14] or who are members of other minoritized groups would take longer to receive tenure.

We calculated time to tenure as the difference between when tenure was conferred and when the respondent was awarded their highest degree. The median time to tenure was 9.3 years. Half of the respondents received tenure between 7.3 and 11.7 years after receiving their highest degrees. Figure 3 depicts the time to tenure by race and ethnicity. The median time for faculty members who identify as Asian/Asian American or as Black/African American was more than 10 years.

Because many factors can affect the length of time it takes faculty members to receive tenure after earning their highest degree, we developed a multivariate model that includes explanatory factors for which we had measures in the survey. They include data about the institution and department where the faculty member is employed, including what type of school it is (public or private); whether it is a historically Black college or university; and what the highest physics degree it offers is. The model also considers personal factors, such as whether the highest degree was earned in the US or abroad; whether the faculty member took a postdoctoral appointment, and if so, how long it was; whether the faculty member's tenure clock was stopped; and what demographic characteristics the respondent possesses, including gender identity and race/ethnicity.

Although the questionnaire allowed respondents to indicate more than one race/ethnicity, a respondent's data may only be included once in a regression model. For that reason, faculty members who indicated that they belonged to more than one minoritized racial and ethnic group were counted as a member of the smaller group. In the analysis, the "another race/ethnicity" category included faculty members who identified as Indigenous, because so few identified that way in the survey.

Time to tenure

Some of the model results, which are summarized in figure 4, are not surprising. For example, faculty members who stopped or extended their tenure clock took about a year longer to receive tenure than those who did not. It also is not surprising that faculty members who took a postdoctoral appointment took longer to receive tenure than those who did not. For every year spent in a postdoc, however, the time to tenure increased by less than a year. That indicates a good return on the time invested in a postdoc.

Our hypothesis that women take longer to receive tenure than men was not supported. In addition, we found no statistically significant difference in time to tenure between faculty members who identify as white and faculty members who identify as Hispanic/Latino, although barriers in the tenure process have been found in qualitative research.[15] The intersecting identities of some faculty members can lead to multiple barriers for them, which could increase time to tenure. When we included intersectionality of gender and race/ethnicity in our model, however, the result was not statistically significant. The lack of statistical significance is likely because of the small number of people in the intersectional groups that were studied, which led to a large standard error in the analysis.

We did, however, find evidence of differences in time to tenure for faculty members who are Black/African American and Asian/Asian American compared with white faculty members. When we control for all the variables in the model, Black/African American faculty members on average received tenure 1.5 years later, and Asian/Asian American faculty members 0.8 years later, than similar white colleagues. The differences are statistically significant.

Black/African American faculty members on average received tenure 1.5 years later, and Asian/Asian American faculty members 0.8 years later, than similar white colleagues.

Mounting evidence

Consistent with research on the barriers experienced by faculty members from minoritized racial and ethnic groups, our results provide quantitative evidence that faculty members who are Asian/Asian American and those who are Black/African American have longer time-to-tenure experiences than faculty members who are white. That may result from the barriers experienced by faculty members who are minoritized. The stereotyping, bias, and unwelcoming environments documented for faculty members who are Black/African American and who are Asian/Asian American may result in cumulative disadvantages, which lead to a longer time to tenure. For example, when faculty members work in unwelcoming environments and are implicitly categorized by stereotypical traits, they may be less likely to be offered opportunities to collaborate. Fewer collaborations may lead to fewer publications and fewer successful grant applications, cumulating in longer time to tenure.

Unfortunately, our quantitative analysis can go no further in specifying the exact causes of the differences in time to tenure. There could be several reasons a faculty member receives tenure later than colleagues. For example, some faculty members could make a request or be encouraged to submit their materials later without a formal "stop the clock" process. The latter "encouragement" may be well-intentioned but could be a result of unconscious biases about the abilities of faculty who are members of minoritized racial and ethnic groups.

Some institutions, for example, automatically give longer time periods to faculty members who are moving from a less prestigious institution or who take parental leave. Faculty members may not think of those delays as stopping the tenure clock, which would have been accounted

	CHARACTERISTIC	REFERENCE CHARACTERISTIC	EFFECT
INSTITUTIONAL	Public school	Private school	✗
	Historically Black college or university	Not an HBCU	✗
	Highest degree department offers is bachelor's	Highest degree is PhD	✗
	Highest degree department offers is master's	Highest degree is PhD	✗
	Respondent earned highest degree in the US	Highest degree earned abroad	✗
PERSONAL	Length of postdoc	No postdoc	✓
	Tenure clock stopped or extended	Tenure clock NOT stopped or extended	✓
DEMOGRAPHIC	Woman	Man	✗
	Asian/Asian American	White	✓
	Black/African American	White	✓
	Hispanic/Latino	White	✗
	Another race/ethnicity	White	✗

FIGURE 4. MULTIPLE FACTORS—including institutional (orange), personal (blue), and demographic characteristics (purple)—could affect how long it takes a faculty member to receive tenure. In our multivariate analysis of faculty survey data, we compared each characteristic in the first column with the reference characteristic in the second column. The green check marks in the third column show which factors had an effect on time to tenure.

for in the model. Another consideration is that faculty members from minoritized racial and ethnic groups may have a more difficult time finding a welcoming institution. They may be more likely, therefore, to change institutions before coming up for tenure, which delays their total time to tenure. None of those factors were measured in our survey.

Ideally, faculty members receive tenure and remain with a department for several decades or more. But as our analysis shows, the process may be far from ideal, since barriers lengthen some people's tenure process. That makes it even more important to continue examining the experiences of faculty members who have not yet received tenure. (For some personal perspectives on being denied tenure, see the article by Toni Feder on page 44.)

A wealth of qualitative research has identified many of the barriers faced by faculty members from minoritized groups. Our results show that researchers need to continue to collect evidence in order to identify the mechanisms by which the barriers translate into a longer tenure process. Once the mechanisms are identified, they can be dismantled. Scientists routinely address hard problems. It is time to include among them the inequitable experiences of faculty members from minoritized groups so that access to tenure is not hampered by bias or barriers.

We are grateful to the physics and astronomy faculty members who completed the questionnaire. We gratefully acknowledge the contributions of John Tyler, who manages the faculty survey data set; Arlene Modeste Knowles and Jovonni Spinner, who reviewed the piece; and an anonymous reviewer, who provided helpful comments.

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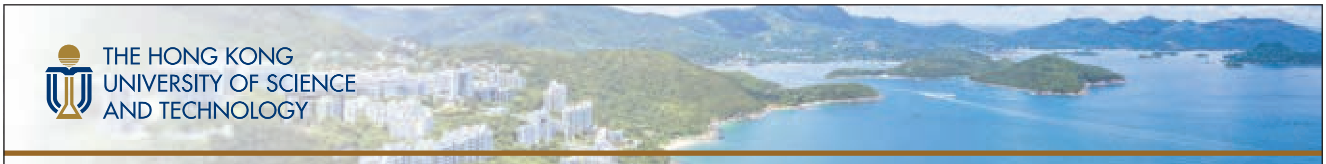
UNIVERSITY OF DENVER

Assistant Professor Tenure-Track Position
Quantum Science/Experimental Condensed Matter

The Department of Physics & Astronomy at the University of Denver (DU) invites applications for a tenure-track assistant professor position to begin in September 2024. We seek candidates with research interests in experimental condensed matter physics whose research and teaching will support an initiative in Quantum Materials and Information Science, launched with one faculty member already hired in 2022. All areas broadly related to quantum materials and information sciences will be considered, with the potential for collaboration with existing research areas on campus and surrounding areas a particular plus. The successful candidate will possess enthusiasm for teaching both undergraduate and graduate courses, and demonstrate promise of developing an independent extramurally funded research program that involves both Ph.D. and undergraduate students. Though we intend to focus on experimental candidates, a theoretical or computational candidate with an exceptionally strong match to the position and the department may be considered.

Applications must be submitted through **https://jobs.du.edu** and should include a cover letter, CV, statements of teaching philosophy and research plans, a one-page diversity statement, and names and contact information for at least three references. Applications completed before January 1, 2024, will be assured full consideration, but the selection process will continue until the position is filled. More information about the department can be found at **https://physics.du.edu**.

The University of Denver is committed to enhancing the diversity of its faculty and staff. We are an Equal Opportunity/ Affirmative Action Employer. All qualified applicants will receive consideration for employment regardless of age, race, color, national origin, religion, sex, sexual orientation, gender identity, disability, or military/veteran status.



TENURE-TRACK FACULTY POSITIONS IN PARTICLE PHYSICS AND COSMOLOGY

The Department of Physics invites applications for several tenure-track faculty positions at the Assistant Professor level in experimental and theoretical physics. The target areas of the search are Theoretical High Energy Physics and Cosmology, Experimental Particle Physics and Observational Cosmology. Applicants must possess a PhD degree in physics or a related field. The successful candidates should have a strong track record of research (the ones with an interdisciplinary background are especially encouraged to apply). Appointments at the rank of Associate Professor or above will be considered for candidates with an exceptional record of research excellence and academic leadership. In addition to pursuing a vibrant research program, appointees are expected to engage in effective teaching at the undergraduate and graduate levels.

The current faculty in the particle physics and cosmology group at The Hong Kong University of Science and Technology include Professor Andrew Cohen, Professor Tao Liu, Professor Kam-Biu Luk, Professor Kirill Prokofiev, Professor George Smoot, Professor Henry Tye, and Professor Yi Wang. The department is expanding its effort in this area by hiring additional new faculty in theory and experiment. Further information about the Department can be found at http://physics.ust.hk.

Starting salary will be highly competitive and commensurate with qualifications and experience. Fringe benefits including medical and dental benefits, annual leave and housing benefits will be provided where applicable. The initial appointment prior to tenure will normally be on three-year contract terms. A gratuity will be payable upon successful completion of a contract.

Application Procedure: Applicants should submit their applications along with CV, cover letter, complete publication list, research statement, teaching statement, and three reference letters.

High Energy Theory and Cosmology (PHYS1017H):
https://academicjobsonline.org/ajo/jobs/16291

Particle Physics Experiment (PHYS1017P):
https://academicjobsonline.org/ajo/jobs/16292

Observational Cosmology (PHYS1017C):
https://academicjobsonline.org/ajo/jobs/16293

Screening of applications begins immediately, and will continue until the positions are filled.

Tenure-track Faculty Position in Experimental High Energy Physics

The Department of Physics and Astronomy at the University of Notre Dame invites applications for a tenure-track faculty position in Experimental High Energy Physics. Applications from exceptional researchers at the associate professor rank will also be considered. The HEP group at Notre Dame consists of 9 experimental and 5 theoretical faculty, doing experimental research with CMS, DUNE, MINERvA, EMPHATIC, and NA61, along with instrumentation and computing R&D. Our theory group does research on low-energy, collider, and astrophysical tests of the Standard Model and its possible extensions. The successful candidate will be expected to complement our efforts either on the CMS experiment or in neutrino physics, and establish leadership within the relevant experimental collaboration(s).

Applicants should submit a curriculum vitae, list of publications, detailed research plans, and a statement of teaching and mentoring. Candidates must also arrange for at least three letters of recommendation. Any application received prior to November 4 being given full consideration.

Apply at: https://apply.interfolio.com/125157

Two Tenure-track Faculty Positions at the Stavropoulos Center for Complex Quantum Matter

The Stavropoulos Center for Complex Quantum Matter at the Department of Physics and Astronomy of the University of Notre Dame invites applications for two tenure-track faculty positions. One position will be theoretical physics and one in experimental physics. Applications from exceptional researchers at the associate or full professor rank will also be considered. The successful candidates are expected to complement current efforts and areas of expertise towards the Center's mission to synthesize materials of interest for novel technologies and to study them with cutting-edge experimental and theoretical methods (https://quantummatter.nd.edu/). The newly established Stavropoulos Center is led by László Forró, the Aurora and Thomas Marquez Chair Professor of Physics. The condensed matter group at Notre Dame consists of 10 experimental and 5 theoretical faculty members, specializing in hard condensed matter, quantum materials, complex networks, and biological physics.

Applicants should submit a curriculum vitae, list of publications, detailed research plans, and a statement of teaching and mentoring. Candidates must also arrange for at least three letters of recommendation. Review of applications will begin on November 15 and will continue until the positions have been filled.

Further information and application details at: https://apply.interfolio.com/131060

We seek faculty members committed to developing and sustaining an environment of inclusive excellence in research, teaching, and service. The successful candidates must demonstrate the ability to develop a highly successful research program, attract independent research funding, teach effectively at both the graduate and undergraduate levels, and engage with students from diverse backgrounds. Applicants must have a Ph.D. or equivalent advanced degree. Salary and rank will be commensurate with the successful applicant's experience and research accomplishments. The expected start date is August 2024.

The department is committed to diversifying its faculty and encourages applications from women and members of traditionally underrepresented groups.

The Department of Physics at Notre Dame has 47 tenured and tenure-track faculty; another 25 research, teaching and concurrent faculty, as well as professors of the practice; more than 110 graduate students; and about 110 undergraduate physics majors. Additional information about the department and the College of Science can be found at http://physics.nd.edu and http://science.nd.edu respectively.

The University of Notre Dame seeks to attract, develop, and retain the highest quality faculty, staff and administration. The University is an Equal Opportunity Employer, and is committed to building a culturally diverse workplace. We strongly encourage applications from female and minority candidates and those candidates attracted to a university with a Catholic identity. Moreover, Notre Dame prohibits discrimination against veterans or disabled qualified individuals, and requires affirmative action by covered contractors to employ and advance veterans and qualified individuals with disabilities in compliance with 41 CFR 60-741.5(a) and 41 CFR 60-300.5(a).

ABIGAIL MALATE

Toni Feder is a senior editor at Physics Today.

WHEN TENURE FAILS

Toni Feder

The prospect of losing out on tenure can be frightening. But many who have been denied tenure have gone on to build successful careers in education or elsewhere.

As an assistant professor at Stanford University in the early 2000s, Adina Paytan brought in grants, trained graduate students, and was a popular teacher. She received an NSF CAREER award and a NASA New Investigator award. She was recognized by the American Geophysical Union for early-career excellence in oceanography. The dean of Stanford's School of Earth Sciences told her she was in the top 20% of faculty in the school. "They told me I was walking on water," says Paytan. So in 2006 the news that she was being denied tenure came as "a total shock."

GLACIOLOGIST DERRICK LAMPKIN, shown here on a trip to Antarctica in 2011, when he was an assistant professor at the Pennsylvania State University. His spectral measurements contributed to the development of satellite-based algorithms for retrieving geophysical properties that document effects of regional warming. Lampkin was denied tenure at Penn State, and again after starting over at the University of Maryland. He is now a scientist at NASA headquarters and NASA Goddard Space Flight Center. (Courtesy of Derrick Lampkin.)

A biophysicist who requested anonymity still keeps with him the letter from a decade ago informing him that he had lost out in his bid for tenure in the physics department of a large, public US research university. It was one of just two tenure denials in that department in 25 years. The news was devastating, he says, and made him question whether he was cut out for a research career.

When the University of Chicago denied tenure to cosmologist Sean Carroll in 2006, he was caught off guard. "These are your friends and colleagues, and now they want you to leave," he says of the department faculty members that voted him out. "I had gotten messages of 'no problem,' but it turns out they thought they could do better," he says.

An assistant professor typically goes up for tenure in their fifth or sixth year on the job. Tenured faculty are guaranteed employment; they can be let go only in extreme circumstances, such as if they commit a crime or their department folds. "I have watched the tenure system up close for 40 years," says Meg Urry, director of the Yale Center for Astronomy and Astrophysics. "It's important because of the vulnerability of people trying to generate new knowledge. Scholars should be free to pursue ideas regardless of whether [the ideas] happen to be popular."

The requirements for tenure involve research, teaching, and service, for which the bar and balance vary. The details are deliberately fuzzy in order to encompass variations across disciplines. An unwritten requirement is that a candidate be a "good fit."

David Helfand has served as chair of astronomy at Columbia University and chairs the board of the American Institute of Physics (publisher of Physics Today)—and has himself steadfastly refused tenure.[1] At Columbia, he says, "there is a 30-page handbook that lays out the rules. But it's always a value judgment."

Tenure denials are uncommon, and statistics about them are scarce. A 2012 study by Deborah Kaminski and Cheryl Geisler tracked 2966 assistant professors in science and engineering fields at 14 US universities.[2] The authors found that about 64% were promoted to associate professor—which typically coincides with earning tenure—at the same institution and that less than half of those were retained, with the median time to departure being 10.9 years. Other studies, including ones cited by Kaminski and Geisler, show that men are more likely to receive tenure or to leave academia, and women are more likely to move to adjunct positions or to be unemployed.[3–5]

Although every case is unique, some patterns have emerged from conversations I have had with a few dozen academics in physics and adjacent fields who were denied tenure, left before going up for it, or have served on committees that decide on tenure. I also spoke with scholars who study tenure and academic climate.

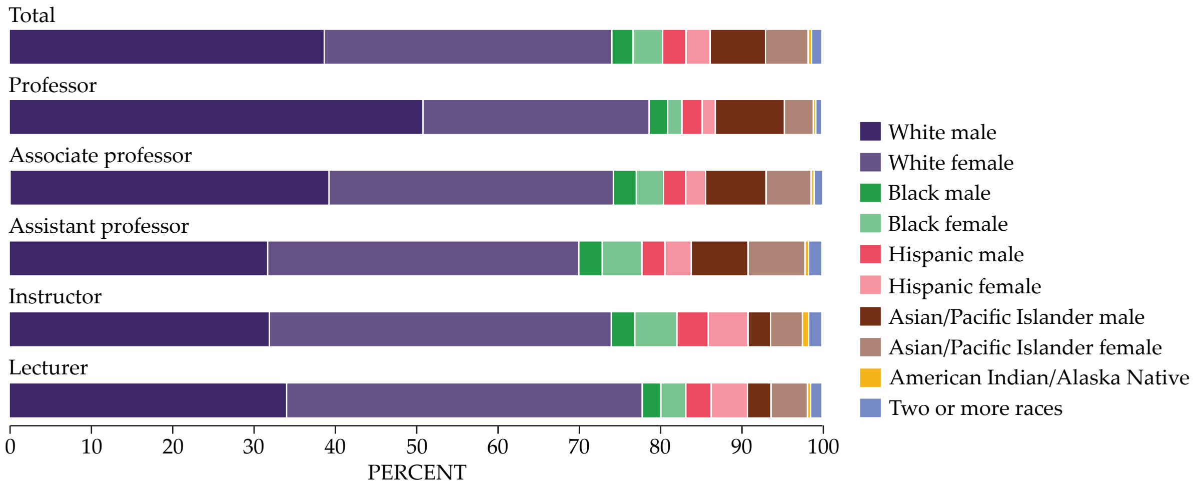
Despite the low numbers, most academics can point to a tenure-denial case or two. From the point of view of an assistant professor aspiring for tenure, says Filomena Nunes, a theoretical nuclear physicist at Michigan State University who has served for years on the College of Natural Science's reappointment, promotion, and tenure committee, even when all seems to be going well "the tenure process induces anxiety."

By the time researchers are on the tenure track, they've made a huge investment in an academic career. The institutions, too, have put in significant time and money in hiring them. At US research universities today, startup packages for new faculty in theoretical physics can be several hundred thousand dollars, and in experimental physics, between $1 million and $2 million is the norm. So what are the implications for assistant professors who are denied tenure or leave before going up for it? And what sorts of careers do those scholars pursue?

Significant statistics

University-wide, Columbia awards tenure 96% of the time, according to Helfand. In astronomy over the last 40 years, he adds, the rate has been nearly 90%. Elliott Cheu, a particle physicist, cites a success rate exceeding 90% in the College of Science at the University of Arizona in 2008–19. For most of that period, he was the associate dean; he is now interim senior vice president for research and innovation.

But numbers like those Helfand and Cheu quote may not be representative of different types of departments and schools, and they exclude people who leave before going up for tenure. That omission skews the broader picture, given that some peo-



FACULTY BREAKDOWN by gender, race, and academic rank is shown for the 1.5 million faculty who worked at degree-granting postsecondary institutions in the US in fall 2020. Of those, 56% were full time, and 44% were part time. At the higher, tenured ranks, white men were better represented than white women and all other groups, but the gender breakdown among nonwhite faculty members is more even than among white ones. Women were equally or better represented than men at the assistant professor level and in the non-tenure-line, lower-ranked positions of instructor and lecturer. (Fast Facts, "Race/ethnicity of college faculty," 2022, https://nces.ed.gov/fastfacts/display.asp?id = 61.)

ple hop off the tenure track because they suspect—or have been advised—that their tenure bids will fail.

Indeed, many faculty and academic administrators say that leaving before going up for tenure is more common than being denied it. In the past 10 years, the Pennsylvania State University has granted tenure to nine people and hired two with tenure in the physics department, says Miguel Mostafá, an astrophysicist and associate dean for research and innovation there. In that same period, he says, there were no denials, but two assistant professors were "gently" urged to move on. In abandoning the tenure track, candidates avoid the stigma of a denial, are more likely to be hired into a nontenured position at the same institution, and retain a higher chance of landing a tenure-track position elsewhere.

"There is a formula for estimating the probability of getting tenure," asserts particle physicist Michael Witherell, who was denied tenure by Princeton University in 1981. "If there are seven times as many tenured as tenure-track faculty, then the probability for tenure approaches 100%." As that ratio drops, so does the rate of awarding tenure, he says, and when the number of tenure-track faculty in a department outnumbers the tenured faculty, the chances of being awarded tenure are slim.

When Witherell was up for tenure at Princeton, it and a few other elite institutions were known for hiring large cadres of assistant professors but awarding tenure to perhaps just one in five, according to several physicists who tried their luck. Denial still stung, says Witherell, although he and most of the others I spoke with went on to have successful careers. For his part, Witherell joined the faculty at the University of California, Santa Barbara, and a few years later was wooed by both Princeton and Harvard University. He served as director of Fermilab for six years and now holds the top job at Lawrence Berkeley National Laboratory.

Unspoken rules

Plenty of evidence shows that underrepresented groups face increased barriers to receiving tenure. At most top universities, Urry says, tenure bids are evaluated on seven criteria: publications, citations, teaching evaluations, letters of recommendation, prizes, invited talks, and grant money. Studies have shown that each of those criteria has been biased against women.[6–8]

"I don't have statistics," says Urry, "but in the departments I've been in, it's the women's cases that get picked on." The interpretation of external letters is "often a highly subjective activity," she adds. Most places also look at service—committee work, mentoring of students, and leadership in diversity, equity, and inclusion initiatives.[9] "My impression is that women do much more service, so maybe it isn't surprising that it doesn't count for much."

The way impact is counted is subjective, says glaciologist Derrick Lampkin, who was twice denied tenure. "It's made to look quantitative—grants, publications, graduates, h-indices, and so on. But people game the metrics." For example, he says, "gaining entrance into groups of colleagues who reference each other's papers and advocate for each other's work among peers will help your numbers. And it depends on your inclusion in the research community."

The tenure process needs to be reformed, Lampkin continues, noting that it "disproportionately results in the loss of women and underrepresented minorities that would have been important in driving the pace and quality of discovery."

NiCole Buchanan is a psychology professor at Michigan State University who studies exclusionary practices in evaluating faculty research. "If you know the rules, the unspoken language of academia, you are deemed more prepared, you are more accepted," she says. People who are not versed in academic culture are more easily excluded—from lunch, collaborative research projects, grant applications, and the like.[10,11] "It's not random who that happens to," says Buchanan. "If you are queer, a woman, or a faculty member of color, you are given subtle and not-so-subtle messages that you don't belong." (For more on how gender, race, and ethnicity affect tenure success rates, see the article by Rachel Ivie and Susan White on page 36.)

SARAH ACIEGO was fed up with academia and left the University of Michigan shortly before she would have gone up for tenure. She has since cofounded Arcus Aero, a company based in Bridgeport, Texas, that restores vintage aircraft. She is shown here with a 1952 DeHavilland Beaver. (Courtesy of Darrin Adkins.)

Exclusionary behaviors spill into attitudes toward research topics, says Buchanan. "Our studies show that when people do work on the margins, it can be identified as groundbreaking and amazing. Or it can be marginalized. That even applies in physics."

Sometimes research may be viewed as too far-out; assistant professors are commonly advised to keep their investigations mainstream. And even when they do so, says Urry, "they can be dinged for not having done something paradigm changing."

The tenure process is nearly always shrouded in secrecy, leaving the denied candidate with incomplete information and a lack of explanation. Even public institutions redact the tenure dossier. Still, the process is more open than it used to be, says Laurence Yaffe, chair of physics at the University of Washington in Seattle. At his university, candidates receive committee reports, redacted summaries of outside letters, and summaries of faculty discussion, and they can respond. "I can't imagine 100% transparency," says Yaffe. The point is to have frank discussions of a candidate's strengths and weaknesses, he says, and in large departments "it's common to have some faculty who don't like the candidate's endeavors."

Only in the rare cases in which a lawsuit is initiated are the inner workings of the process revealed. Most of the time an understanding of the outcome is dominated by the vantage of the candidate—and even that is limited to candidates who are willing to share their experiences. As Carroll says, "I wasn't in the meetings. I don't really know why I was denied tenure."

Still, details often trickle back to professors whose tenure bid has been denied. Or they may piece together explanations from what they know of their own performance and experiences, their department, and their university.

Missteps to tenure

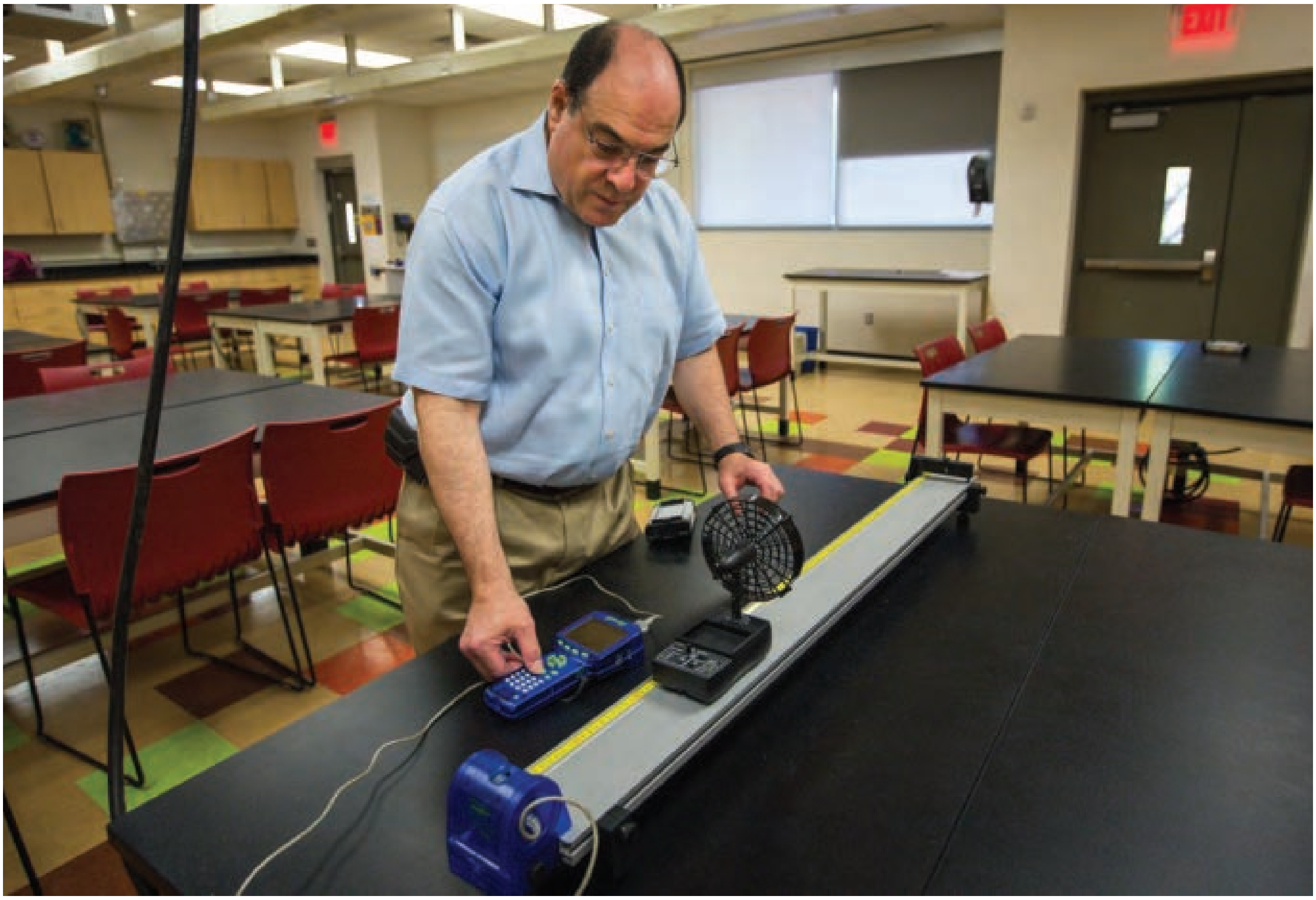
"To me it seems that roughly 5–10% of candidates are so good, they have to get tenure," says Urry. A similar percentage of candidates hasn't produced enough to win tenure, she continues, "but the vast majority could go either way, depending on how people spin it. It's kind of arbitrary."

"In many cases the people who are denied tenure are as good, and sometimes better, than the ones who get tenure," says Urry.

Aside from rare clear-cut cases of inadequate research or teaching, tenure may be denied if a candidate is perceived to be spending excessive time on activities that don't count toward tenure. Carroll believes that writing a textbook figured into his denial.[12]

Tenure might also be denied if a powerful faculty member feels threatened by the research of a more junior colleague. Becoming mired in departmental politics can thwart a candidate's promotion prospects. So can introducing innovative teaching methods, which voting faculty may see as criticism of their own approaches. Based on interviews, denials in the US to noncitizens and to people hired into the tenure track directly out of graduate school seem disproportionately high, perhaps in part because such candidates are less tuned into the academic systems they join.

A person's bid for tenure can fail if a department loses interest in their subfield—even one they were hired to build up.



David Meltzer was hired with tenure in 2008 at Arizona State University. In 2016 he joined the university's College of Integrative Sciences and Arts, where he continues to focus on physics-education research. He had previously been denied tenure in physics at Iowa State University. (Courtesy of Arizona State University.)

For cases in which an assistant professor is supported by an outside entity, a department may be grateful for the temporary funding stream—or it may take advantage of the free teaching and drop the person when the tenure decision comes around and the department is expected to step in with financial support. Lampkin suspects that's what happened to him in the department of atmospheric and oceanic science at the University of Maryland in 2019.

Lampkin's first tenure-track position was at Penn State, straight out of graduate school. He had collaborations, publications, students, and more than $1 million in grants. But, he says, he lacked the network and political intuition that he might have had as a white man or someone from a family steeped in higher education. He had been brought in as a diversity hire, he says, and as he later learned, the department chair had offered him the job before holding a faculty vote, which may have caused resentment. When the tenure decision went against him, Lampkin says, the dean told him, "Your colleagues don't want you here. You are not a good fit. But you will do a great job elsewhere."

He started over at Maryland. There, he says, his research continued to flourish, but for four years he was not assigned to teach in his own research area—something he would need for his tenure bid. Moreover, Lampkin says, his tenure case was rife with procedural errors, such as his department's losing his third-year review, which had been positive and was supposed to be part of the package. During his appeal of the denial, a colleague who was upset with the process leaked details, says Lampkin.

The denials themselves were devastating, Lampkin says. "I lived through protracted depression. It placed severe emotional and financial stress on my family. It impacts your whole life." Today Lampkin provides program science support to NASA and keeps a hand in research.

Paytan likewise attributes her denial to sabotage on the part of a more senior colleague and to campus politics that dissuaded other faculty from intervening on her behalf. The colleague had "said out loud that he'd make sure I wouldn't get tenure," she says. She had also spoken out on other issues, like maternity leave for students. "It's an issue of personality. I managed to piss off someone with power," she says.

"Despite my documented success in research and teaching, my department was dysfunctional and was not willing to stand up to the 'sabotaging' person," says Paytan. When Stanford denied her tenure, students from the department protested.

Paytan now works at the University of California, Santa Cruz, in the Institute of Marine Sciences. Not on a tenure line, she supports a large research group on grants. The work climate at Santa Cruz is better, she says, and she calls her tenure denial a "blessing in disguise. I wouldn't have left Stanford otherwise." With nearly 17 000 citations, she is currently ranked 204th in the US and 362nd in the world among the top 2000 Earth sciences researchers by Research.com. Being denied tenure "was devastating," says Paytan. "But it did not damage my career because I always knew that it was not me, but the system, that is bad."

Exiting pretenure

Ingrid Novodvorsky joined the physics department at the University of Arizona in 1999 as part of a new program to train high school science teachers. The chair favored building up physics-education research in the department, she says. "But once I got into the department I realized that wasn't a common opinion."

Novodvorsky says she "never got much research mentoring" and that hostility in the department was obvious: "Walking down the hall and nodding hello and being ignored was not subtle." She saw that the senior physicists resented her introducing "evidence-based teaching—clickers, peer teaching, and other stuff we know makes learning effective."

Her third-year review was favorable, but by 2005, the writing was on the wall. Her department chair and the director of the teacher preparation program suggested she move into a position that would report directly to the associate dean. She took the job, happy to continue working in education. She never went up for tenure. "It didn't seem worth the risk."

In 2010 Sarah Aciego started a tenure-track position at the University of Michigan in the department of Earth and environmental sciences. Her research was in isotope geochemistry on ice cores. Things "went sideways quickly," she says. Soon after she started, a colleague with whom she was supposed to share a lab departed, leaving the responsibility for it on her shoulders. A flood in a clean room hiked costs and delayed her getting the lab up and running by two years. Later, Aciego had a graduate student who "wasn't willing to be mentored by me." Her department insisted she continue as his adviser, she says.

Despite the setbacks, Aciego had won a prestigious Packard fellowship and other grants, and she was advising students, doing research, and publishing. But, she says, "I was being dragged down and not getting support from my department. It was like death by a thousand cuts."

Aciego started a business leading tours in extreme environments. She took up flying. Then she left her tenure-track job to manage a 10 000-acre dude ranch with 50 horses and 400 cattle. She also worked as a freelance editor. Now she and her partner have a business restoring vintage aircraft near Fort Worth, Texas. Her goal is to fly an air ambulance for a children's hospital. Aviation, she says, "is technical and uses scientific curiosity to solve problems."

Being awarded tenure would have been a recognition of her performance. But she knew she wanted to leave academia. Says Aciego, "It felt dishonest to put my friends and colleagues through the work of evaluating me."

Academic and adjacent paths

Many scholars who are denied tenure or leave before going up for it stay in higher education in non-tenure-line positions. Some teach at middle or high schools or at community colleges. They also go to industry, government, and publishing. And some get tenure at another—usually less prestigious—institution. A complete pivot from physics and education seems rare, or at least harder to identify, based on those interviewed for this article. I did hear of a couple of people who decided to leave the workforce.

The anonymous biophysicist stayed in academia and is coming up for tenure again soon. A particle physicist I spoke with has worked at Fermilab for many years since he was denied tenure at the University of Illinois. "There is still stigma," he says, explaining his request for anonymity.

David Meltzer attributes having been denied tenure in 2004 by Iowa State University to a combination of the physics department's having second thoughts about physics-education research, which he had been hired to set up there, and "a personal element." He fought the denial in both the university and the courts, taking his case all the way to the Iowa supreme court. For a while he worked in Lillian McDermott's research group at the University of Washington and briefly taught at a middle school. Burnt out from his experiences in academia, he was willing to take a university job only if it came with tenure. After landing an offer at Arizona State, he says, "my world changed. I went from the prospect of collecting unemployment insurance to having a secure job with a salary of $85 000."

In 2018, the president of a minority-serving institution turned down the tenure bid of a physical chemist after the college-wide committee voted in his favor. After union-backed litigation, the physical chemist, who wants to remain anonymous, was awarded tenure and back pay. He is now tenured at a different institution.

Geochemist Maureen Feineman felt "demoralized" when she stepped off the tenure track at Penn State in 2012, about a year after returning from maternity leave. "Having a child while on the tenure track can lower chances of success for a variety of reasons," she says. She stayed on at the university as a research professor. For six years she headed the department's undergraduate program, and she now runs an electron microprobe lab, teaches, and does research. While on the tenure track, she says, "No matter how hard I worked, it was never enough. I was always behind, rushing to catch up. That never let up. Now I can choose what I want to focus on." She does not have job security, she notes, but her pay is comparable to that of someone with tenure. "In the long run, I've been a much happier human than I would have been in a tenured position."

After tremendous investments of time and money, says Lampkin, it should be no surprise that people who have been denied tenure—"a population of highly trained and motivated individuals"—find ways to "creatively recover and move our lives forward in new trajectories."

Even so, a sense of shame and bitterness often persists after tenure denial. But "professors who do and don't get tenure are equally happy five years later,"[13] according to Harvard University psychologist Daniel Gilbert, who has conducted several studies on the subject.[14]

Departments lose too

Tenure denials can be bad for departments, too. Small departments, in particular, may be short on instructors for a year or more after someone is denied tenure. And the department—or a subfield—could lose the tenure-track position completely.

And a denial can hurt faculty morale. “Departments do not want a reputation for chewing up assistant professors and spitting them out,” says Columbia’s Helfand. He and others note that the real gatekeeping occurs at the hiring stage: “We only hire assistant professors we expect to tenure. And then we support them with everything—space, resources, and mentoring,” Helfand says.

“After we have gone through an elaborate search process, why should we change our minds about someone?” says Michigan State University’s Nunes. “So my question is, if someone doesn’t get tenure, what did the institution do wrong?” Often, she says, the failing is a lack of mentoring. Academics are not trained as mentors, and many scientists “think of mentoring as a waste of time,” she says. “Academics can be a bunch of prima donnas, not a community that takes care of each other.”

Many university administrators and academics describe the tenure system as robust and usually fair. A department “might feel it has to deny tenure occasionally, otherwise it looks like standards have fallen,” says Carroll, who is now in a named non-tenure-line professorship at Johns Hopkins University. He has also written popular science books and been involved in other forms of science outreach. Still, he adds, “I wish departments were more risk-taking and experimental and less conservative.”

Urry calls the tenure system “terrible,” but says she “can’t think of a better one.” A physicist who was denied tenure and prefers anonymity says, “Tenure is necessary. Without it, the university system would crumble. Scientists would go to other sectors for higher-paying, less stressful jobs.”

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Tenure-Track

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The Department of Physics and Astronomy at the University of Missouri, Columbia (MU) invites applications for a tenure-track faculty position at the rank of Assistant Professor, beginning on August 1, 2024.

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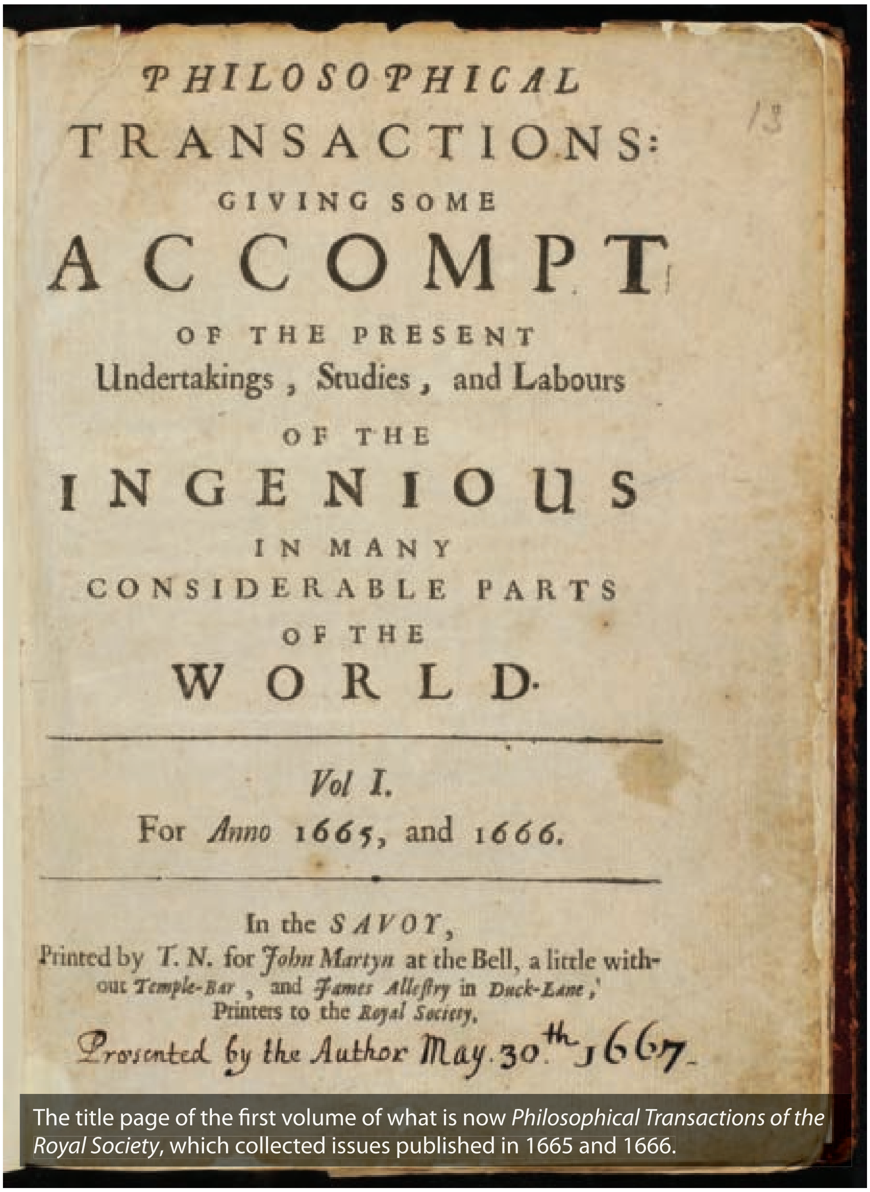

PHILOSOPHICAL TRANSACTIONS: GIVING SOME ACCOMPT OF THE PRESENT Undertakings, Studies, and Labours OF THE INGENIOUS IN MANY CONSIDERABLE PARTS OF THE WORLD.

Vol I.

For Anno 1665, and 1666.

In the SAVOY,
Printed by T. N. for John Martyn at the Bell, a little without Temple-Bar, and James Allestry in Duck-Lane,
Printers to the Royal Society.

Presented by the Author May 30th 1667

The title page of the first volume of what is now *Philosophical Transactions of the Royal Society*, which collected issues published in 1665 and 1666.

History of a publishing colossus

In March 1665 Henry Oldenburg, the secretary of the recently founded Royal Society of London, presented a sample issue of a periodical to the society's council. As one of Oldenburg's colleagues told the great Dutch natural philosopher Christiaan Huygens, the new journal was intended to publish "philosophical matters . . . from overseas" as well as reports of "any experiments, or at least the most important ones" in Great Britain. Today, the journal now known as *Philosophical Transactions of the Royal Society*—often abbreviated as *Phil. Trans.*—is still in print. It is now one of many long-running journals published by the society.

Despite the Royal Society's long-standing place in the landscape of scientific publishing, however, until last year there was no comprehensive history of its journals. Individual historians had focused on specific pieces of that story,

A History of Scientific Journals

Publishing at the Royal Society, 1665–2015

Aileen Fyfe, Noah Moxham, Julie McDougall-Waters, and Camilla Mørk Røstvik
UCL Press, 2022. Open access ($90.00 hardcover)

analyzing episodes such as the foundation of the *Phil. Trans.* in the 17th century, the major financial and editorial changes it experienced in the 18th, and the 19th-century establishment of the society's second journal, *Proceedings of the Royal Society of London*.

But it took a team of scholars, funded for multiple years by the UK Arts and Humanities Research Council, to produce *A History of Scientific Journals: Publishing at the Royal Society, 1665–2015*. This impressive piece of historical scholarship not only makes a significant contribution to the history of scientific publishing but also illustrates the remarkable possibilities of historical collaboration and open-access publication.

A History of Scientific Journals is organized chronologically: Every era of Royal Society publishing is discussed in detail. Interested in why *Philosophical Transactions* split into series A and B in the late 19th century? Want to know more about the foundation and evolution of *Notes and Records*, the society's history of science journal? Curious about how the society has handled the 21st-century transition to digital publishing? It's all here, described in clear prose and carefully documented with well-chosen quotes from the society archives.

I am especially impressed by the work the authors have done to reconstruct the finances of the Royal Society's journal-publishing operations. The team carefully traces how journal publication went from an expense that the society shouldered on behalf of its members to one of the society's primary sources of income. Financial discussions among Royal Society members and leaders often led to debates about the value and purpose of journal publication. A seemingly mundane decision in the 1950s about whether the society should continue to pay Cambridge University Press to market their journals, for example, revealed that the society's members were uneasy over the role of for-profit publishers in scientific publishing.

A History of Scientific Journals covers those debates in detail, giving us financial specifics, names and histories of Royal Society officers, and snippets from correspondence in the Royal Society archives. There are also flowcharts for editorial workloads, which illustrate how decisions about which articles to publish have at various times been made by editors, Royal Society fellows, external referees, or some combination of the three. That level of nuance and detail can, at times, make for slow reading. It is a delight for those, like myself, who are invested in the history of scientific periodicals, but those with only mild curiosity will likely find the book daunting. Even historians may find themselves focusing on some chapters while skimming or skipping others. But given that it is available open access, complaining that the book has too much detail would feel like complaining that a free buffet has too much food.

There are four credited authors on *A History of Scientific Journals*: Aileen Fyfe, a professor and historian of science at the University of St Andrews, and Noah Moxham, Julie McDougall-Waters, and Camilla Mørk Røstvik, who all worked on the project as postdoctoral fellows. Scientists, of course, are accustomed to publishing papers that include professors, postdocs, and graduate students as coauthors, but a multiauthored monograph is still unusual in history. Promotion and tenure for historians usually depend on single-authored scholarly books, and scholars in the field usually focus on projects they can execute alone or with the help of a few short-term research assistants.

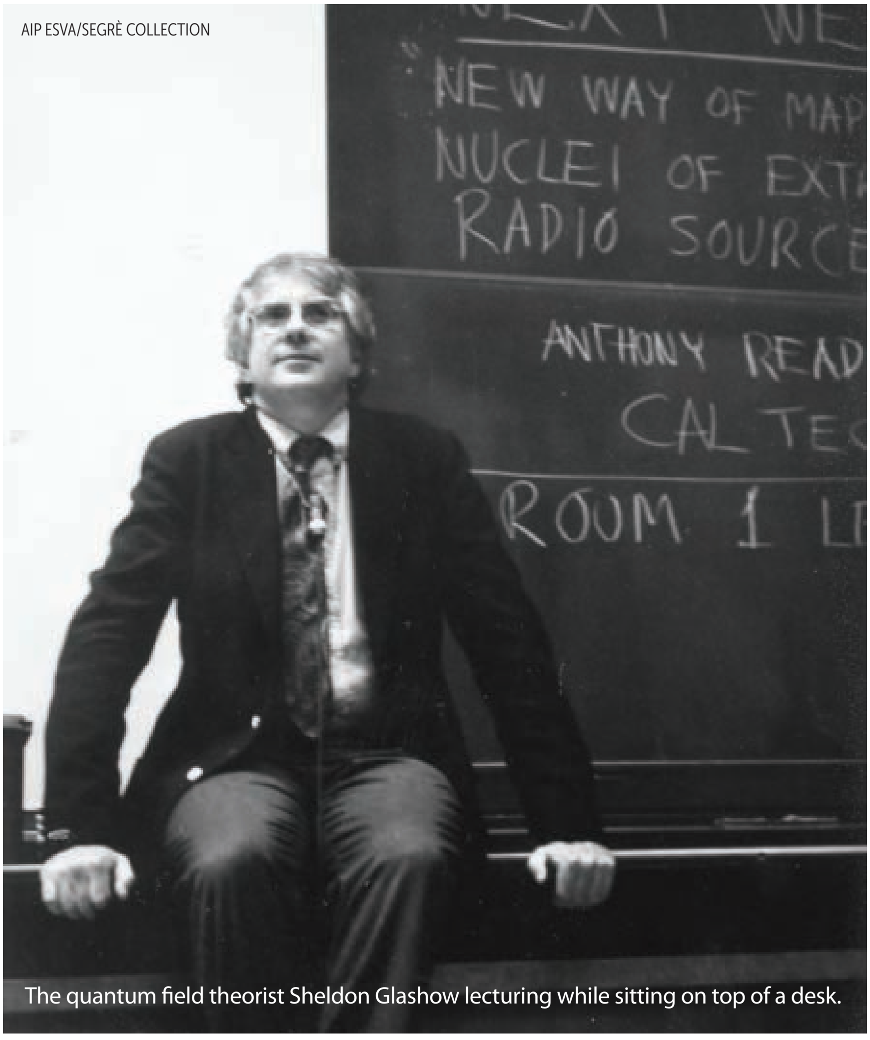
A History of Scientific Journals makes a strong case for the value of more collaborative work. I do not think it would have been possible for a single historian, however dedicated, to produce such a detailed or wide-ranging study. It took multiple authors with different areas of expertise to bring this volume to life, and the book shows the possibilities of cooperative work in the humanities.

Finally, it's worth noting that *A History of Scientific Journals* was published not only physically but also digitally, in a superb open-access version. I wrote this review using only that free digital copy, and it is the most user-friendly scholarly e-book in my collection. Many open-access e-books require readers to individually download each chapter, and most of the scholarly e-books I've paid actual money for don't have hyperlinked footnotes or indexes, which means a lot of cumbersome navigating back and forth. *A History of Scientific Journals*, however, is available on the UCL Press website as a single, hyperlinked PDF, which makes it easy to navigate. I hope other academic publishers take note.

I recommend this book without hesitation to anyone interested in scientific publishing, in any era of history. It is an exciting scholarly achievement, available at no cost to readers.

Melinda Baldwin
University of Maryland
College Park

AIP ESVA/SEGRÈ COLLECTION



The quantum field theorist Sheldon Glashow lecturing while sitting on top of a desk.

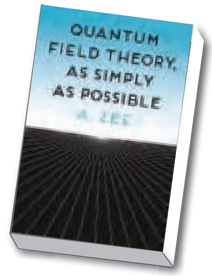
The standard model for beginners

The 2000-year quest to find nature's basic building blocks, which began with Democritus's atomic hypothesis, has culminated in the quantum field theory (QFT) known as the standard model of particle physics. The standard model vastly outperforms its unpretentious name: It is a self-consistent mathematical theory of quarks and leptons, which make up all ordinary matter, and their fundamental interactions. It provides the basic rules that govern elementary particles, atoms, molecules, and even living things.

In his new book, *Quantum Field Theory,*

Quantum Field Theory, as Simply as Possible

A. Zee
Princeton U. Press, 2023. $39.95



as Simply as Possible, theoretical physicist A. Zee provides an overview of QFT aimed at both aspiring theorists who haven't yet taken their first course on the subject and dedicated laypeople who remember high school math and are willing to grapple with the book's heady concepts. As the title suggests, this volume is not for everyone. But those readers who are willing to think deeply will be rewarded with a rich conceptual understanding and appreciation of what Zee somewhat hyperbolically calls the "greatest monument to the human intellect." For example, they'll understand that all electrons—and, for that matter, all other particle species—are truly identical because they are described by a single quantum field. Sweet.

Zee's book is divided into six parts. Each contains a preview, three to six bite-size chapters, and a recap. He leads readers on a journey that generally proceeds chronologically through the history of physics, from the time of Galileo Galilei and Isaac Newton to the present. Part 1 begins with the physics of forces and particles and ends with spacetime and special relativity.

Part 2 opens with the Euler–Lagrange formulation of classical mechanics, which is followed by a discussion of the action principle and the path-integral formulation of quantum mechanics. Diving deep into the path-integral approach is a big plus for a book that is conceptual and not computational, because it beautifully connects classical and quantum physics. Zee impressively succeeds in conveying the essence of the approach without drowning readers in complex mathematics: He only asks readers to remember what integrals are.

Parts 3 and 4 are the heart of the book. They begin with a discussion of force carriers, before moving on to quantum fields, quantum electrodynamics, and Yang–Mills gauge theory. After successfully navigating those parts, the reader will be a conceptual quantum field theorist—or, at the very least, will appreciate the majesty of QFT.

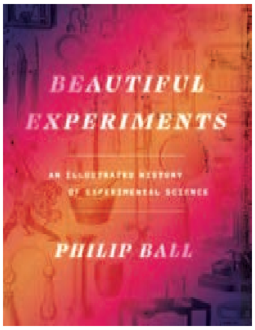
Part 5 pushes the audience to its limits and discusses two triumphs of QFT: antimatter and the standard model. It also discusses quantum field theorists' unfulfilled aspirations to create a Grand Unified Theory that describes all the standard model's forces. Zee then gives readers a bonus by describing Albert Einstein's general relativity—even though it is not a QFT—and the challenges of quantizing gravity. He ends the book with a cooldown in part 6, which compares QFT with quantum mechanics and assesses QFT's intellectual completeness and its shortcomings.

Beyond the clarity of his explanations, his illuminating conceptual diagrams, and his boxed bits of wisdom, Zee has a strong voice that makes the long journey both interesting and personal. It comes out in anecdotes, historical passages—many of which are based on Zee's recollections—footnotes, and endnotes. He includes wonderful stories about giants that we know and he worked with, including Richard Feynman, Julian Schwinger, Sheldon Glashow, and Steven Weinberg; but he also includes depictions of physicists who are less well known, such as his PhD adviser, the late Sidney Coleman, who was the premier quantum field theorist of his generation.

Despite its breadth, there are things you won't find in Zee's book. Although he mentions the Higgs mechanism, Zee doesn't discuss the Higgs boson, its discovery, or its mass—or, for that matter, the mass of any other particle. Save for a few speculations about grand unified theories, which occupied a significant part of his own research, Zee sticks to what has been established: Unlike many popular books about particle physics, he eschews any discussion of string theory and the multiverse.

Quantum Field Theory, as Simply as Possible is a theorist's account of the rise of the standard model. Zee is the ideal person to tell that story, as his career coincided with the triumph of QFT, and he was an important participant in its development. Whether or not readers agree that QFT is humanity's greatest intellectual achievement, they will come away with a deeper understanding of theoretical physics, an appreciation of what QFT is, and an esteem for its elegance.

Michael S. Turner
University of California, Los Angeles



Beautiful Experiments

An Illustrated History of Experimental Science

Philip Ball

U. Chicago Press, 2023. $35.00

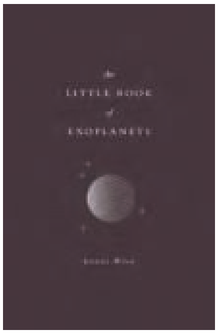
Although experimentation is arguably the backbone of modern science, historians of science have often tended to focus their studies on theoretical developments. The science writer Philip Ball aims to rectify that disparity in his new book *Beautiful Experiments*, which outlines 60 investigations carried out from antiquity to the present day. Ball groups the experiments into six chapters, each of which focuses on themes, including the behavior of organisms, the nature of light, and the nature of life. He complements those efforts with five meditative interludes that delve into philosophical or aesthetic topics relating to experimentation, such as how to define an experiment, why thought experiments are useful, and what scientists mean when they say an experiment is beautiful. The richly illustrated book is a treat for the eyes. —RD

The Launch Party

Lauren Forry

Zaffre, 2023. $6.99 (ebook)

In this sci-fi twist on the classic locked-room mystery, 10 people have won the chance to spend two weeks in the first hotel on the Moon. The first hint of trouble comes almost immediately upon arrival, when they discover that they are alone in the hotel—there's no clerk at the front desk nor bellhops in the lobby, and the spaceship that brought them there has departed. Because a scrumptious meal has been laid out on the buffet and the bar is fully stocked, the guests assume it's a publicity stunt and that they are to proceed as normal—until one of them is found murdered. Fortunately, Detective Penelope Strand of Scotland Yard's murder squad is among the guests, and she initiates an investigation while they await a rescue party from Earth. —CC



The Little Book of Exoplanets

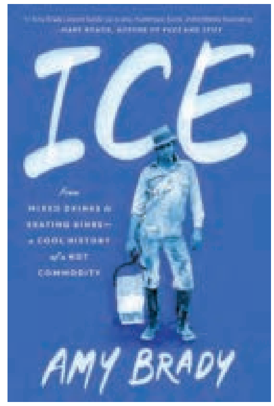
Joshua Winn
Princeton U. Press, 2023. $22.95

Since the 1990s, thousands of exoplanets have been detected. They run the gamut from Earthlike planets to exotic worlds far different from any in our solar system. In *The Little Book of Exoplanets*, astrophysicist Joshua Winn discusses what has been learned about exoplanets so far and the techniques used to make those discoveries, as well as current theories concerning planet formation, examples of unusual exoplanet systems, and predictions about what new technologies and spacecraft may discover. Aimed at the nonspecialist, the book provides a brief overview of the field while keeping mathematical equations and technical language to a minimum. —CC

Ice

From Mixed Drinks to Skating Rinks—A Cool History of a Hot Commodity

Amy Brady
G. P. Putnam's Sons, 2023. $29.00

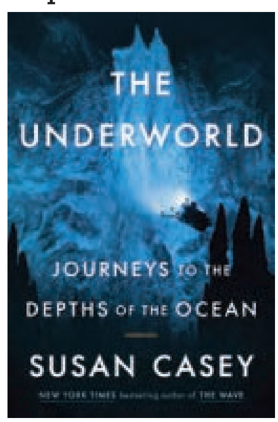


Until about 150 years ago, ice was generally available only to those who lived in cold climates. In her new book, journalist and historian Amy Brady discusses the meteoric rise of the ice industry in the US, due in part to innovations in transportation and manufacturing but mostly to the efforts of ambitious entrepreneurs whose extensive marketing efforts spurred consumer demand. Brady discusses the harvesting of ice from lakes and rivers; ice's importance in food and drink, medicine, and sports; and some of the surprising ways it has impacted American culture, including the shortening of women's skirts and the creation of such business chains as 7-Eleven. —CC

The Underworld

Journeys to the Depths of the Ocean

Susan Casey
Doubleday, 2023. $32.00



In *The Underworld*, journalist Susan Casey—not only a writer but also a competitive swimmer and scuba diver—takes the reader to the deepest parts of Earth's ocean. Having traveled all over the world and joined crews on multiple deep-sea missions, Casey vividly depicts the thrills and dangers of voyaging into the ocean's abyss and profiles some of the intrepid explorers who have participated in such ventures. Through her firsthand accounts and engaging prose, Casey draws the reader into a world of exploration as magical and awe-inspiring as that of the NASA astronauts in the early days of the space program. —CC PT

NEW PRODUCTS

Focus on test, measurement, quantum metrology, spectroscopy, and spectrometry

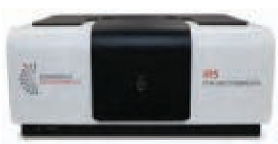
The descriptions of the new products listed in this section are based on information supplied to us by the manufacturers. Physics Today can assume no responsibility for their accuracy. For more information about a particular product, visit the website at the end of its description. Please send all new product submissions to ptpub@aip.org.

Andreas Mandelis

Microspectrophotometer for materials analysis

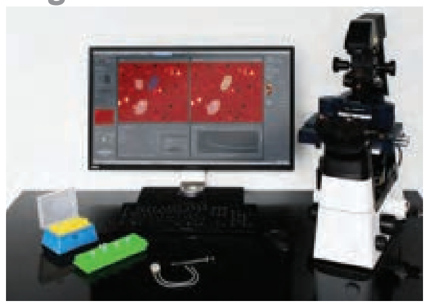
Craic Technologies has announced its 2030XL PRO microspectrophotometer for the nondestructive analysis of microscopic areas of very large samples. The instrument features state-of-the-art optics, a new high-sensitivity spectrometer, and advanced software for fast, accurate data analysis. The flexible 2030XL PRO can analyze a wide range of materials, including semiconductors, flat-panel displays, and biological samples. Multiple measurement modes let users perform absorbance, reflectance, fluorescence, and Raman spectroscopy in one platform. Advanced imaging capabilities allow researchers to visualize samples while obtaining spectroscopic data. The versatile 2030XL PRO is compatible with a wide range of accessories, including microscopes, probes, and sampling tools. ***Craic Technologies Inc****, 948 N Amelia Ave, San Dimas, CA 91773, www.microspectra.com*

FTIR spectrometer



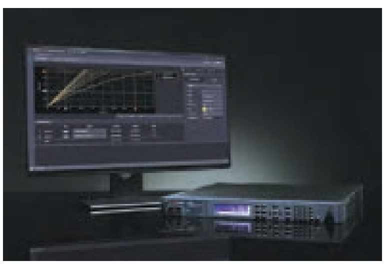
To expand its molecular spectroscopy portfolio, Edinburgh Instruments has brought to market its first Fourier-transform IR (FTIR) spectrometer. The IR5 is offered with options that increase its functionality and make the compact instrument suitable for a wide variety of applications. It can be configured with a second detector to achieve higher sensitivity at selected spectral ranges or with a Fourier-transform photoluminescence (FT-PL) capability with a choice of laser source. The FT-PL option converts the IR5 into a combined absorption and PL spectrometer in the mid-IR range so that it can be used in demanding research applications. The IR5 features high sensitivity and spectral resolution; simple operation suitable for beginning to advanced users; moisture-control technology that eliminates the need for maintenance; and powerful, intuitive Miracle software designed specifically for the IR5. ***Edinburgh Instruments Ltd****, 2 Bain Sq, Kirkton Campus, Livingston EH54 7DQ, UK, www.edinst.com*

Force measurements for single-molecule research



Bruker's ForceRobot 400 BioAFM for force measurement features an increased level of automation and advanced optical techniques. It can be seamlessly integrated into the latest research-grade optical microscopes with advanced and super-resolution capabilities. The ForceRobot 400 generates over 250 000 force curves per day to deliver the statistically significant data sets required for demanding discovery and preclinical research. It offers advanced force-curve profiles and label-free, nanomechanical measurement of individual molecules in near-physiological conditions. The flexible SmartMapping functionality allows for the investigation of user-defined areas. To advance the design and synthesis of novel macro- and nanomaterials, the ForceRobot 400 enables the study of the mechanical properties of natural and synthetic polymers at the single-molecule level. The highly accurate motorized sample stage and large-scale Z-motors allow for the continuous evaluation and automated adaptation of the acquisition range. ***Bruker Nano GmbH****, JPK BioAFM Business, Am Studio 2D, 12489 Berlin, Germany, www.jpk.com*

High-density source measure unit



Keysight's new source measure unit (SMU) is designed to speed up semiconductor characterization. Featuring high-channel-density precision, the PZ2100 series SMU solution offers up to 20 SMU channels in a 1U full-width form factor that does not require cooling spacers when stacked. By simplifying channel stacking and synchronization, it not only removes integration and coding complexity but also saves time. The graphical user interface accelerates test prototyping, debugging, and troubleshooting, and the PathWave IV Curve measurement software enables quick measurements and synchronization without programming. The compact, scalable PZ2100 series reduces cost by integrating pulser and digitizer functions with conventional SMU functions, such as precise DC voltage and current sourcing and measuring. Available in five SMU-configurable, upgradable options, the all-in-one module for integrated circuit design characterization meets emerging requirements without additional instruments. ***Keysight Technologies Inc****, 1400 Fountaingrove Pkwy, Santa Rosa, CA 95403-1738, www.keysight.com*

Broadband RF amplifiers for equipment testing

Rohde & Schwarz has expanded its BBA300 ultra-wideband RF amplifier family by adding a powerful 90 W model for its CDE and DE series products. The robust BBA300 amplifiers provide stable, precise test signals for electronic compatibility and coexistence testing and for testing components during development and production. They offer up to 250 W output power. The BBA300-CDE offers a continuous frequency range from 380 MHz to 6 GHz; the BBA300-DE operates from 1 GHz to 6 GHz. Their very broad frequency range makes the amplifiers suitable for wireless and ultra-wideband applications. Software options let users optimize the transmission characteristics for specific applications so they can evaluate devices in multiple ways in a single test without changing equipment. Amplitude, frequency, phase, pulse, and complex orthogonal frequency-division multiplexing modulation modes are supported. ***Rohde & Schwarz GmbH & Co KG**, Mühldorfstrasse 15, 81671 Munich, Germany, www.rohde-schwarz.com*

Software for quantum computer integration

Quantum Machines and ParTec, located in Munich, Germany, have co-developed a universal software solution for the integration of quantum computers into high-performance computing (HPC) environments. According to the companies, QBridge is the first commercially available solution that enables multiple HPC users to seamlessly execute hybrid workflows across HPC classical and quantum computing resources. Tightly integrated with Quantum Machines' OPX classical–quantum controller, QBridge helps HPC users improve performance from hybrid classical–quantum systems. It allows for programming of advanced multiqubit algorithms that require robust classical processing. To provide insights into the quantum system and maximize usability, the QBridge quantum stack is transparent and flexible. It caters to various users, from circuit-level for algorithm developers to low-level pulse control for quantum researchers. ***Quantum Machines**, HaMasger St 35, Tel Aviv-Yafo, 6721407, Israel, www.quantum-machines.co*

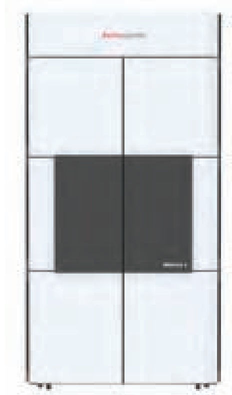
Fiber laser for quantum research

NKT Photonics has launched its Koheras Adjustik HP T20 fiber laser optimized for barium ion ($^{138}Ba^+$) excitation at 1762.17 nm. According to the company, barium ions are suitable for quantum computing: It is easy to manipulate the ions' electrons with laser beams and use them as qubits. Designed specifically for the 6S-to-5D transition in barium, the Koheras Adjustik HP T20 is a rack-mountable, benchtop, distributed-feedback (DFB) fiber-laser source. Based on the company's industrial Basik DFB fiber lasers, the Koheras Adjustik HP T20 is a stable, all-fiber, low-noise, mode-hop-free laser with a free-running linewidth of 10 kHz. It offers robust single-frequency operation and a high power of 500 mW at 1762.17 nm. The built-in fiber-delivery solution preserves the low-noise laser properties and delivers single-mode light at all wavelengths. The Koheras Adjustik HP T20 is suitable for such applications as qubit manipulation, quantum sensing, and sympathetic cooling. ***NKT Photonics Inc**, 23 Drydock Ave, Boston, MA 02210, www.nktphotonics.com*

Single-column universal testing machines

Mecmesin, a PPT Group brand, has added three single-column models with capacities of 0.5 kN, 1 kN, and 2.5 kN to its OmniTest range of universal testing machines (UTMs). The UTMs can perform static tensile and compression testing of metals, plastics, polymers, alloys, composites, wood, fabrics, glass, laminates, and ceramics in R&D and quality assurance in a wide range of industries. They occupy minimal bench space and, weighing less than 30 kg, can be easily transported. The 2.5 kN model is suitable for general-purpose testing; the 0.5 kN and 1 kN models have extended column lengths that make them appropriate for long-elongation, low-force testing. The company's VectorPro testing software drives the versatile OmniTest UTMs; the PC-driven model can run the test routines on users' chosen computer hardware. ***Mecmesin/PPT Group UK Ltd**, Newton House, Spring Copse Business Park, Slinfold, West Sussex RH13 0SZ, UK, www.mecmesin.com*

Semiconductor metrology



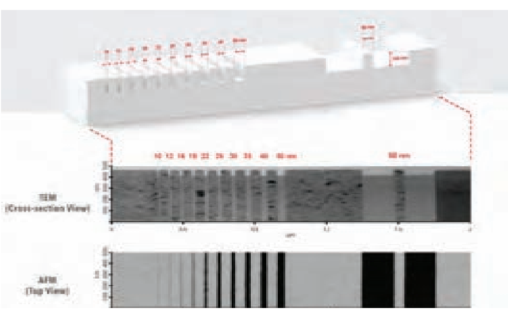
The latest version of Thermo Fisher Scientific's scanning transmission electron microscopy (STEM) metrology solution for high-volume semiconductor manufacturing improves average productivity by up to 20% compared with the previous-generation instrument. The Metrios 6 (S)TEM incorporates state-of-the-art hardware and machine-learning algorithms to rapidly obtain large-volume, high-quality data from complex devices and novel materials. New features and capabilities include the fully automated Smart Stage mechanism for sample insertion and retraction. By eliminating manual operation and thereby the potential for human errors, it speeds up high-resolution imaging. The company's new Ultra-X energy-dispersive spectroscopy (EDS) detection system offers fast compositional characterization and elemental mapping to ease challenging analysis on the most beam-sensitive materials. A newly designed objective lens and source innovations enable voltage switching in minutes versus hours, higher-efficiency STEM and EDS acquisition, and high resolution. ***Thermo Fisher Scientific Inc***, *168 Third Ave, Waltham, MA 02451, www.thermofisher.com*

Universal streak camera

The C16910 universal streak camera from Hamamatsu is an ultrahigh-speed detector that captures light-emission phenomena occurring in extremely short time periods. Its temporal resolution is less than 800 fs. Combining a sweep unit and a function-expansion unit, the camera can detect a single photon and can measure various phenomena by capturing either single shots or multiple shots at high repetition rates. It features wavelengths from the UV to the near-IR and simultaneous measurement of light intensity on temporal and spatial (wavelength) axes. The internal multi-controlled-phase (MCP) gate improves the signal-to-noise ratio. By using the MCP and the photocathode gates together, the camera can achieve an extinction ratio of 10^8 or more. Applications include fluorescence-lifetime measurement, optical communications, research involving free-electron and other types of pulsed lasers, plasma-light emission, and lidar Thomson scattering. ***Hamamatsu Corporation***, *360 Foothill Rd, Bridgewater, NJ 08807, www.hamamatsu.com*

Atomic force microscope for battery research

Oxford Instruments Asylum Research has introduced an atomic force microscope (AFM) configuration for battery research. The Cypher ES Battery Edition combines the ultrahigh-performance Cypher ES AFM with a fully sealed, three-electrode—working, counter, and reference—electrochemistry cell constructed from highly chemical-resistant materials. BlueDrive photothermal excitation is included and allows for simpler, more stable imaging in liquids; fast scanning enables the capture of dynamic processes. The Cypher ES Battery Edition features high stability and resolution even when integrated with a glove box for lithium battery research and is available with sample heating and cooling. A versatile tool, it can be used to optimize battery performance and characterize the electrode–electrolyte interface at the nanoscale. For example, it can monitor the formation and stability of solid–electrolyte interphases and probe electrical double-layer structures. ***Oxford Instruments Asylum Research***, *7416 Hollister Ave, Santa Barbara, CA 93117, https://afm.oxinst.com*



Traceable calibration standards

To facilitate accurate sample measurement and analysis, Park Systems now offers its NANOstandard product line for reliable calibration of atomic force microscope (AFM) and scanning electron microscope systems. According to the company, the Park NANOstandard is equivalent to NIST-traceable products for measuring the critical dimensions of semiconductor patterns, among other materials. The NANOstandard products include the AFM tip characterizer (AFMTC) and high magnification calibrator (HMC). Designed to evaluate the radius and half-cone angle of an AFM tip, the AFMTC calibration sample is nanopatterned with linewidths ranging from 10 nm to 50 nm. The HMC standard sample is made of polycrystalline silicon and has five certified linewidth values ranging from 20 nm to 80 nm and five certified pitch values ranging from 100 nm to 900 nm. The standards conform to the Korea Research Institute of Standards and Science for ISO 17034:2016 and are traceable through the atomic lattice constant in the silicon substrate by high-resolution transmission electron microscopy. ***Park Systems Inc***, *3040 Olcott St, Santa Clara, CA 95054, https://parksystems.com* PT

John Bannister Goodenough

John Bannister Goodenough, who pioneered studies of magnetism, orbital physics, electronic and ionic transport in transition-metal compounds, and materials for energy storage, died on 25 June 2023 in Austin, Texas. He was a corecipient of the 2019 Nobel Prize in Chemistry. At the time of his death, he was a professor at the University of Texas at Austin, where he had been since 1986.

Born on 25 July 1922 in Jena, Germany, to American parents, John and his family moved to Connecticut when he was an infant. He went to Groton School in Massachusetts as a teenager and developed his sense of morality and religious commitment from its headmaster, Endicott Peabody.

John was admitted to Yale University in 1940. With World War II raging, he enlisted in the US Army in 1942. John received a BA in mathematics in spring 1943, and he began serving as an army meteorologist that fall. Egbert Miles, his mathematics professor at Yale, changed the trajectory of John's career by adding John's name on the list of veterans recommended to do graduate studies in physics or mathematics.

John obtained his PhD in physics from the University of Chicago in 1952 under Clarence Zener. Although John did not publish any articles with Zener, Zener's research style can be traced throughout John's papers. And discoveries they each made contributed to the portable-electronics technologies that have changed our everyday life: the Zener diode in miniature chargers and John's cathode materials for lithium-ion batteries in computers and cell phones.

After receiving his PhD, John began a 24-year career at MIT's Lincoln Laboratory. As a team leader, he worked on the magnets used in magnetic RAM. He identified the relationship of magnetic domain-wall dynamics and dynamic Jahn–Teller (JT) distortion in the spinel oxides. That finding led to an ideal square-shaped magnetic-hysteresis loop. When John had the opportunity to reorganize a solid-state research group at the lab, his golden time in science began.

John adopted the JT theorem for molecules in solids by introducing cooperative JT distortions. He rationalized the rich magnetic orderings of perovskite oxides by connecting the subtle structural change and orbital occupation through cooperative JT distortions. In a milestone in magnetism, John demonstrated spin–spin exchange interactions based on orbital degrees of freedom. His picture of orbital ordering and charge ordering beautifully explained the magnetic ordering and the structural distortions in the perovskite $La_{1-x}Ca_xMnO_3$. John's 1955 article on the topic in *Physical Review* was published back-to-back with the neutron experimental paper by Ernest Wollan and Wallace Koehler.

John summarized his groundbreaking approaches in magnetism, as described by the now-famous Goodenough–Kanamori rules, in his 1963 book *Magnetism and the Chemical Bond*. The rules provide the most practical guidance for researching the magnetic materials that are behind numerous technologies, including today's 6G communications.

John established models for a microscopic understanding of physical properties of transition-metal compounds at the time when many scientists were puzzled by why an oxide becomes a metal. He introduced concepts of electron itinerancy through covalent bonds and the first-order localized–itinerant transition, and he constructed the energy diagram based on the electronic configurations and crystal structures. Materials physicist Sang-Wook Cheong tells the story of when he once proposed studying physics in manganites to his boss: He was told, "It has been well done by John Goodenough a long time ago. He left nothing for us to do."

John's appointment as head of the inorganic chemistry laboratory at Oxford University in 1976 caused some controversy because he was a physicist with no formal chemistry training. His students often had difficulties connecting the dots between their typical chemistry courses and John's lectures, although some later looked back on his teaching with admiration.

Throughout his career, John discussed physics by illustrating some compounds and their connections. As he would often say, he would "do

HADI KHANI

John Bannister Goodenough

chemistry to solve physics problems." When the 1970s energy crisis hit, John turned his attention to materials for energy storage. He led the inventions of three major cathodes for lithium-ion batteries. Those discoveries were made not because of chance but because of John's fundamental understanding of the physics and chemistry involved. An overdue call from Stockholm in 2019 was a reward for his lifetime contributions to science.

John loved interacting with young researchers. He would tell them, "I would not have sat in this chair if I hadn't learned from my students." Even into his 90s, John never thought to slow down. He came to his office with fresh ideas every day. He would say, "I have an aged body but a heart like a child." Determined to solve problems and have a positive impact on society, John never changed how he pursued science: "My feet are on engineering; my heart is on science."

John wrote in his 2008 book *Witness to Grace*, "Love can create peace out of discord; it can and does create remarkable (miraculous?) changes in human health and character." John's life was a perfect testament to that statement. A giant in science and a model citizen, John will be greatly missed.

Jianshi Zhou
University of Texas at Austin

Benjamin Breneman Snavely

Benjamin Breneman Snavely, who expertly merged engineering principles with physics during his diverse and productive career, was born in Washington, DC, in January 1936. He followed his father on a scientific career path; Benjamin L. Snavely worked for the US Navy on underwater acoustic instruments and techniques.

After receiving his BS in electrical engineering from Swarthmore College in 1957, Ben earned an MS in electrical engineering from Princeton University in 1959 and a PhD in engineering physics from Cornell University in 1962. He worked as an intern at the US Naval Ordnance Laboratory during his undergraduate summers and at IBM during his graduate summers.

Ben spent more than two decades at Eastman Kodak. His responsibilities involved optics, lasers, and materials science. His best-known Kodak contribution was to the early development of the dye laser, including the first demonstration in 1970 of its continuous-wave operation.

Because of his expertise in tunable and high-power lasers, Ben took a sabbatical in 1973–76 to work at Lawrence Livermore National Laboratory. There he coled the laser isotope separation program.

On his returning to Kodak, Ben managed many critical projects in its federal systems division. His efforts led to the development of the first large-area CMOS optical detectors, which are now routinely used in nearly every telescope application and in cell-phone cameras.

Because of its work on large-area mirrors, Kodak produced the primary optics for several major telescope projects. Ben led his team in developing ion-beam figuring in 1988 and making it operational in 1990. It has been called the most important breakthrough ever in optical manufacturing. The mirrors on the Keck telescopes were finished using the process. Ben's other projects included developing spy satellite mirrors and the *Hubble Space Telescope*'s backup mirror now housed at the Smithsonian Institution.

KEVIN B. MARVEL

Benjamin Breneman Snavely

After retiring from Kodak in 1991, Ben parlayed his experience with telescopic optics and other technology into an eight-year stint as NSF program director for advanced technologies and instrumentation in the astronomical sciences division. He led the planning and funding of numerous projects that resulted in new optical observatories and technology for astronomy. His extensive scientific and technical background, coupled with his knowledge of industrial and government laboratories, proved invaluable. Among his other NSF activities were the continued enhancement of CMOS detectors and the early development of IR array detectors, adaptive optics and the use of laser guide stars, and the use of optical interferometry. He was most proud of efforts to initiate searches for exoplanet systems, a now-blossoming field that has identified and studied thousands of such systems in ever-greater detail.

While at NSF, Ben also spent two years assisting President Bill Clinton's administration on its program to reinvent and simplify how the public and outside organizations interact with the federal government.

Ben's last career stop was at the American Institute of Physics (AIP; publisher of Physics Today), where for 15 years, beginning in 1999, he served as corporate secretary. Three of us (Dylla, Lanzerotti, and Marvel) had the pleasure of getting to know Ben as we worked together on various projects. We three most appreciated Ben's wide-ranging experience with how physicists can contribute to our field, whether in academic, industrial, or government settings. Ben's NSF work with the Clinton administration benefited AIP as the institute reinvented and reformed its somewhat ponderous governance structure as an umbrella organization serving 10 scientific societies and their 120 000 members. Ben's quiet, thoughtful advice and counsel was especially helpful to the AIP board chair (Lanzerotti).

Ben was a passionate and talented sailor and pilot. His pride and joy was a 36-foot Sabre named *Iteration*. Ben, with his son and others, won several sailing races with *Iteration*. He greatly enjoyed planning summer cruises on Lake Ontario with family and friends. His favorite location was near the small Canadian island of Waupoos. Some of his and his sailing companions' fondest memories were of watching the Moon rise over the island on a cool night, after an afternoon thunderstorm, and enjoying a glass of wine in the cockpit. One moonless night while gazing at the myriad of stars, Ben was shown the faint smudge of light from the nearby Andromeda galaxy, visible to the naked eye under the right conditions. Ben grabbed his binoculars and was in awe at what he was seeing for the first time. Optics, astronomy, and his love of science came together in that moment.

When Ben retired for good in 2014, he spent more time doing his two favorite pastimes: building and flying model airplanes and sailing his boat. We and all of Ben's colleagues, friends, and family lost Ben when he died peacefully in his home in Alexandria, Virginia, on 5 September 2022.

H. Frederick Dylla
American Institute of Physics
College Park, Maryland
Louis J. Lanzerotti
New Jersey Institute of Technology
Newark
Kevin B. Marvel
American Astronomical Society
Washington, DC
G. Wayne Van Citters
National Science Foundation
Alexandria, Virginia PT

Kristin Poinar is an assistant professor in the department of geology at the University at Buffalo in New York.

Small lakes could destabilize Earth's ice sheets

Kristin Poinar

In Greenland and Antarctica, pools of meltwater are one of many threats to the ice sheets' longevity.

At the poles, unlike elsewhere on Earth, the day–night cycle lasts a full year rather than 24 hours. Annually, each pole has a single sunrise and a single sunset. Such a year of extremes guarantees long winters and summers intense enough to melt some, but not all, of the snowfall. The cycle gives rise to the planet's ice sheets.

The Greenland Ice Sheet holds an amount of water equivalent to 7 m of global sea-level rise, while the East and West Antarctic Ice Sheets lock away 60 m. Summertime meltwater is plentiful in Greenland, but in Antarctica, it is found only around the fringes.

On the ice sheets, natural surface depressions collect meltwater into lakes—a few kilometers wide and a few meters deep—as shown in figure 1. Without the depressions, meltwater would run off the ice into the ocean. But instead, the water in the lakes can short-circuit that overland path by fracturing the ice sheet. Because of the density inversion between ice (920 kg/m^3) and the meltwater (1000 kg/m^3), the only requirements for such an ice-sheet rupture are a preexisting fracture and enough water to fill it. The weight of the water is focused at the fracture tip, and as long as new water flows in to maintain overpressurization, it forces the tip ever deeper.

The same technique—fracking—is used by the oil and gas industry. In that case, however, drillers must artificially pressurize the water to fracture shale rocks, whose density is 2500 kg/m^3. On ice, gravity alone is sufficient.

Lakes can speed up ice glide

Ice in the Greenland Ice Sheet flows in two ways: by deforming, which moves ice tens of meters per year, and by sliding atop water that lubricates its base, which moves ice several kilometers per year. Some 95% of that water comes from the surface through fractures, many of which are initiated at supraglacial lakes. Those fractures occur quickly: In just a few hours, they propagate hundreds of meters deep and drain about 10^{10} liters of water to the bed, with water flux exceeding that over Niagara Falls.

Underneath the ice, the arriving water produces a fluid-filled blister that jacks up the ice locally and eliminates the ice–bed friction that usually resists ice flow. Over time, the water diffuses outward, the blister decays, and friction returns, but the initial perturbation induces important temporary changes.

The surface is uplifted about 1 m, and the speed of the ice increases enough to stretch the ice by 0.1–1% per year. If the accompanying induced stresses exceed the tensile strength of ice, new

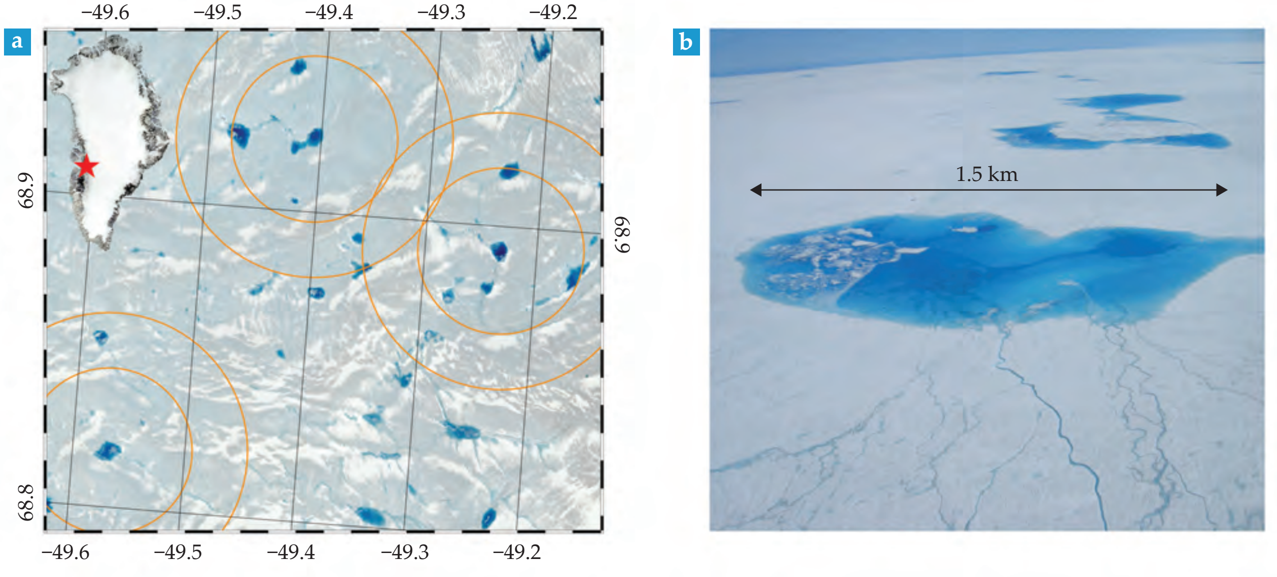


FIGURE 1. SUPRAGLACIAL LAKES (a) within a 20 × 20 km area (red star in the inset) of the Greenland Ice Sheet are imaged by satellite on 12 June 2018. Orange circles around three of those lakes mark the estimated 3–5 km radius where one lake drainage can induce another. **(b)** This supraglacial lake is pictured before the water fractures the ice.

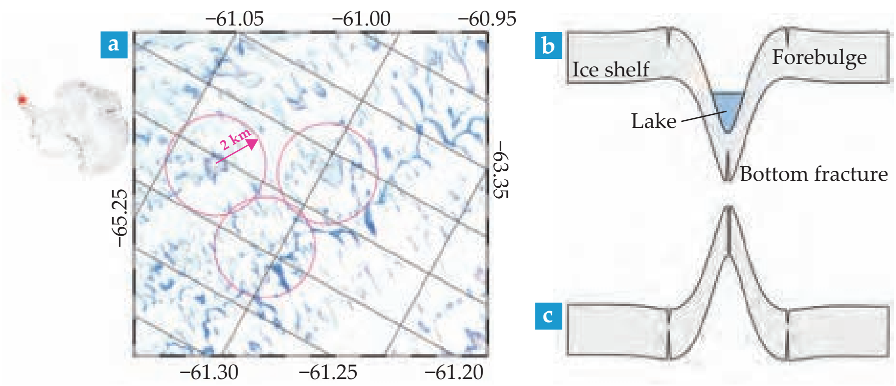


FIGURE 2. ON THE LARSEN B ICE SHELF in Antarctica, **(a)** supraglacial lakes in a 14 × 14 km area are imaged by satellite on 21 February 2000, two years before the ice shelf's disintegration. Pink circles show the 2 km flexure radius from three lakes. **(b)** An idealized profile of an ice shelf is pictured before collapse, with a lake and the features it induces: a central basin and a radial forebulge 2 km away and tens of centimeters high. Surfaces in extension are prone to fracture. **(c)** A profile of the same area is pictured after the lake's drainage induces isostatic rebound and inverts the forebulge, where new fractures form at the same sites but on the opposite surface.

fractures appear in and around the lake basin. Crucially, if those fractures coincide with a second lake, that lake water can fracture ice to the bed, which can produce another blister that may open new fractures in other lake basins and drain them as well. Observations bear that process out: Every summer, clusters of a dozen or so Greenland lakes drain within a few days of each other.

Those events are controlled by two length scales: (A) the distance over which the water blister creates new surface fractures, and (B) the distance between lakes. The estimated range of A (3–5 km) exceeds that of B (1–2 km) and thus allows a wave of lake drainages that propagates both down-glacier and up-glacier. As the wave proceeds down-glacier, A generally increases while B decreases, making it likely that all lakes down-glacier will drain.

Approximately 100 km inland from the coast, however, B rises above A; the lakes are spaced too far apart to intersect the fractures induced by the water blister. But in the near future, as the climate warms and the ice sheet thins, A will increase and the intersection point will move farther inland, causing new lakes to drain. That, in turn, will send water to drier inland areas of the bed, where the subglacial water system is less well developed or even absent. The process could, in theory, make the ice slide faster into the sea and thus thin the ice sheet further.

Are waves of lake drainages a tipping point for ice-sheet stability? Possibly, but it is a slow mechanism: It relies on viscous ice flow to thin the ice and lower the surface to elevations where summer temperatures exceed 0 °C and meltwater lakes can form. Total destruction of the ice sheet that way could take thousands of years. Other mechanisms that can destroy an ice sheet, such as icebergs calving into a warmer ocean, happen more rapidly. Importantly, the time scale of destruction of the Greenland Ice Sheet is primarily sensitive to the rate at which Earth warms. More anthropogenic warming and thus a faster time scale—perhaps just 1000 years—seem likely, but so far no process has tipped the system into instability.

Lakes can disintegrate ice shelves

At Earth's opposite pole, Antarctica is ringed by ice shelves—floating extensions of the great Antarctic ice sheets. Because the ice shelves are floating, some 90% of their ice is underwater, leaving their surfaces only dozens of meters above sea level. That low elevation means warmer temperatures and meltwater in the austral summer.

The Larsen B Ice Shelf on the Antarctic Peninsula once hosted thousands of meltwater lakes each summer, as shown in figure 2a. The weight of such lakes on a floating ice shelf produces elastic flexure, which creates both a lake basin and a surface deformation known as a forebulge that rings the lake, as shown in figure 2b. The flexure strains the bottom surface of the ice shelf beneath the lake and the top surface at the forebulge. As before, sufficiently large induced stresses can form fractures, which any spatially coincident lake water can drive through the ice shelf to drain into the ocean below. Removing the water load prompts the lake basin to rebound, much like a rubber popper toy that pops from a concave shape to a convex one. The rebound inverts the system into an upward-doming lake bed and downward-bending forebulges, as shown in figure 2c.

Accordingly, stress-induced fractures form on the bottom of the new forebulges, directly below the original fractures. If a second lake coincides with the fractures, they may drain the water. That occurred on the Larsen B Ice Shelf in 2002. Hundreds of lakes drained in just a few weeks by forming a checkerboard of rifts that disintegrated the ice shelf.

Before 2002 the ice shelf resisted the flow of the glaciers feeding it. Its disintegration increased the seaward ice flux in those glaciers by 50%, although the flow speeds have relaxed toward their initial values. Fortunately, the ice shelf catchment was only 6300 km^2, the size of Delaware; total sea-level rise induced by the ice-shelf collapse and the glacier response in the ensuing 21 years is less than 1 mm. Compare that with the 14 million km^2 of Antarctic glacial ice as a whole, which has contributed 8 mm of global sea level rise since 2002, most of it caused by warmer ocean waters accelerating ice flow in West Antarctica.

Some 60% of Antarctic ice is up-glacier of an ice shelf, which would make it vulnerable to acceleration if the ice shelf were to be lost. The Ross and Filchner–Ronne Ice Shelves, which collectively buttress 40% of the continent, currently see virtually no surface melt. They are also significantly thicker than the Larsen B, so flexures and fractures are inhibited. Disintegration of those major ice shelves by lake-induced flexure would require both ice-shelf thinning and additional atmospheric warming that are likely centuries to millennia away. At least four ice shelves on the Antarctic Peninsula, however, have collapsed through that mechanism. As in Greenland, the fate of the remaining ice shelves is tied to future atmospheric warming.

Additional resources

► A. F. Banwell, D. R. MacAyeal, O. V. Sergienko, "Breakup of the Larsen B Ice Shelf triggered by chain reaction drainage of supraglacial lakes," *Geophys. Res. Lett.* **40**, 5872 (2013).
► L. A. Stevens et al., "Greenland supraglacial lake drainages triggered by hydrologically induced basal slip," *Nature* **522**, 73 (2015).
► J. Stock, "Modeled patterns of crevassing induced by supraglacial lake drainage in western Greenland," MS thesis, U. at Buffalo (2020). PT

BACK SCATTER

Fanning flames

This photo shows the ceiling of a 2.4-meter-wide bathroom in a four-bedroom house a few hours after research engineer Matt DiDomizio and his team at the Underwriters Laboratories' Fire Safety Research Institute started a fire in the house's living room, about 10 meters away from the bathroom. The blaze rapidly grew and developed to such an intensity that the heated air, which was unable to easily pass through the nearby closed bathroom door, entered the HVAC system, which was off during the test.

The sooty air that rushed through the bathroom's ceiling vent plunged toward the floor before rising back up. The hot air deposited solid soot particles on the ceiling in a pattern of lighter and darker bands. The dark circular spots are from soot collecting in water vapor that condensed on the ceiling. The light–dark pattern stems from unstable convection, in which a colder fluid—here, air cooled by the ceiling—is partly blocked from descending by hotter fluid below. (Courtesy of Steven Marino.) —AL